

# **Accelerating Innovation: Assessing Nanotechnologies, Prototypes & Research Teams**

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# **Accelerating Innovation: Assessing Nanotechnologies, Prototypes & Research Teams**

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## **Abstract**

The Army-sponsored Institute for Soldier Nanotechnologies (ISN) was an entrepreneurial research institute established at the Massachusetts Institute of Technology (MIT) in 2002. Using Science and Technology Studies (STS) concepts from Actor-Network Theory, I study the founding era of this twenty-first century laboratory-based community, from 2002-2007. Actor-Network concepts of enrollment and translation, described by Bruno Latour, and heterogeneous engineering, described by John Law, are used as I 'follow the actors' founding this emergent institution. The operationalization of translation is traced through four case studies, structured around Defense funding constructs and Science and Technology communities: 6.0 Founding the Institute; 6.1 Building Basic Research Networks; 6.2 Shaping Applied Research for Cancer Research and Science Education to include non-users; and 6.3 Student Prototyping Teams Accelerating ISN Research for Traumatic Brain Injuries (TBI). Scientists, engineers, and transitioners partnered in new ways to transition innovative technologies to improve human protection, with soldiers as the first of many users. Using public information, I used qualitative and quantitative methodologies to assess the actor networks and research portfolio changes. These historical case studies extend STS with operationalization of translation and a new dynamic of bi-directional actor enrollment, as research teams transitioned nanotechnologies and prototypes.

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## **General Audience Abstract**

The Institute for Soldier Nanotechnologies (ISN) was an Army-sponsored entrepreneurial research institute established at the Massachusetts Institute of Technology (MIT) in 2002. This historical study examines the founding era, rarely described for start-up organizations. Science and Technology Studies (STS) concepts of Actor-Network Theory enrollment and translation are traced through four case studies: Founding the Institute; Building Basic Research Networks; Shaping Applied Research for Cancer Research and Science Education to include non-users; and Student Prototyping Teams Accelerating Research for Traumatic Brain Injuries (TBI). The scientists, engineers, and transitioners partnered in new ways to transition technologies to improve human protection, with soldiers as the first of many users. Using public information, I provide qualitative and quantitative methodologies to assess the social networks of actors, as well as the composition and changes in the research portfolio. These case studies show **what** the ISN members did and **how** the small teams innovated, operationalizing translation through enrollment, and transitioning nanotechnologies and other prototypes.

## **Acknowledgements**

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## **Note on Data Sources**

Public data available as of April 2019 sourced my research. A key focus area for me was understanding what data was being lost: organizations combine or disappear, and information formerly held in tangible archives was posted to non-permanent web sites. In addition to footnote citations, the following sources were central. Fair Use determination documents are provided in the attached file.

Figure 2: ISN Research Summaries captured by the Internet Archive ‘Wayback Machine’: The original MIT ISN website (<https://web.mit.edu/isn/research/>) was repeatedly captured by the Internet Archive, acting as a non-profit digital library. More than 450 ISN research summaries on different dates provided the corpus for my quantitative portfolio analysis. First capture on Internet Archive was 20 February 2003, at 4:25:29 am (first 8 digits identify capture date, next 6 digits indicate time to seconds): <https://web.archive.org/web/20030220042529/https://web.mit.edu/isn/research/>

Figures 3, 7, 12, 13, 24, 26, 27, 30: ISN Key Soldier Capabilities and Organization Partners, in “Emerging Technologies from the Army-Funded Institute for Soldier Nanotechnologies,” presented by Army Major Rex Blair, NDIA Pacific Operational Science & Technology Conference, Honolulu, Hawaii, 4 April 2007.

Graphs, tables, and computer-generated social network analysis images were created by the author unless otherwise stated.

# Chapter 1.

## Introduction and Research Motivations

### Overview

The Institute for Soldier Nanotechnologies (ISN) was an entrepreneurial start-up research institute established at the Massachusetts Institute of Technology (MIT) in 2002. This twenty-first century laboratory community created technologies for transition to defense and commercial uses. How the ISN community members enrolled participants and partners illustrates a range of approaches to transition-focused science and engineering. Current-day analysts, whether research sponsors, potential partners or competitors, or citizen-scientists, can learn from the patterns of enrollment that led to technology transitions.

Origin stories offer useful insights into how an entity or organization emerged. The starting era shapes culture and processes, but rarely do entrepreneurial start-ups document this phase. Every situation holds many possible outcomes, which may be judged as more or less successful according to different observers' criteria. However, before judging or engaging in post-hoc critiques, examination of the origin story can suggest how the current instance emerged. Choices present in the making undoubtedly shaped the results. Other choices and constraints could lead to different outcomes.

This study is my examination of the origin story of the ISN as an entrepreneurial center. The US Army Research Office held a competition, and MIT bested 50 other universities to win the opportunity: establish a strategic research institute focused on creating nanotechnologies to improve human protection. Soldiers were the first customers, but the expectation was that these materials would protect other humans and

provide broad social benefits. To accelerate technology transitions, the ISN contract required public-private partnerships between MIT, industry, and Army researchers, and a vigorous outreach effort. Just as the Internet emerged from Department of Defense investments in science and technology, the Army hoped that this new material-focused research institute would produce technologies to transform America in the new century. Echoing Vannevar Bush's goals advocated at the end of World War II in "Science – The Endless Frontier," this new institute was established to use basic science to create and publish new knowledge, improve human health, create jobs, and train people in science and technology.<sup>1</sup> The ways and means to achieve these goals differed, but those goals shaped this institute. Research teams organized around the different communities and practices associated with Defense funding categories – 6.0 for initiation, 6.1 for basic research, 6.2 for applied research, and 6.3 for prototypes – and collaboratively co-created new networks, new science, and new technologies that improved human protection.

The most significant challenge I faced in this study was access to the historical data. Unlike previously funded research efforts, the ISN results were not extensively published in the Defense Technical Information Center ([www.dtic.mil](http://www.dtic.mil)), the official Defense repository for science and engineering. The ISN founding team used many other communications channels, publishing in fee-for-access scientific journals and exploring early Internet-age communications. As an analyst looking back at the first ISN contract period from 2002 through 2007, my analysis had to exploit data still available in 2019. This institute emerged during a major socio-technological transition: the accelerated

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<sup>1</sup> Vannevar Bush, "Science -- The Endless Frontier: A Report to the President" (Washington, DC: Office of Scientific Research and Development, July 1945), <https://www.nsf.gov/od/lpa/nsf50/vbush1945.htm>.

growth of the Internet era. The economic crises of the 'dot-com' bust only delayed, not ended, the transition of knowledge to Internet-accessible repositories. Tools that researchers today take for granted, including social network analytics and text mining tools, did not then exist. Google was founded as a company in 1998 to index the Internet for search, and had not yet embarked on the large-scale scanning of data that makes current Internet searches so richly rewarding. TED Conferences existed since 1984, but the widespread and free dissemination of these TED Talks by Internet video was only beginning. Free video viewing by YouTube did not exist until 2005. Facebook, which became a powerhouse lead user and creator of the types of quantitative graph analytics I used to analyze the ISN actor-networks, started in 2004. The not-for-profit Internet Archive Wayback Machine, provided to view old websites as they existed at specific moments in time, began in 2001. The dynamic changes in the data landscape to date suggest that data available today, to any interested viewer using an Internet browser, may not be available in the future. This study peers through a window back in time, showing how today's data can be used to gain insights at a distance.

From the perspective of a Science and Technology Studies (STS) analyst, the ISN would have provided an intriguing venue for in-person laboratory studies, such as Bruno Latour performed when embedded into the Salk Institute in the 1970s.<sup>2</sup> Written as a member of the scientific team performing research and translating data by inscription into publications to persuade outsiders, his ethnographic study examined micro-transactions between scientists to create facts. No such STS analyst was on staff or on site during the

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<sup>2</sup> Bruno Latour and Stephen Woolgar, *Laboratory Life: The Construction of Scientific Facts* (Princeton, NJ: Princeton University Press, 1979).

initial start-up phase of the ISN. This historical analysis could inform the perspectives of interested outsiders, separated from the institution's founding by many years. Such an outside viewer could be a federal research sponsor, seeking to reinforce desirable outcomes for a similar research institution, or to identify obstacles to technology transitions that should be reduced. A different perspective could be viewed by a competing university, seeking to understand what made MIT appealing as the site of this research establishment in order to increase their own relative positioning to win future research grants. Yet another perspective could be that of a researcher at a historically disadvantaged university, seeking to increase opportunities for scholars from many backgrounds to participate in leading-edge research. Citizen-scientists could seek to understand research done by the nation on their behalf, using their tax dollars. Yet another perspective could be the STS researchers advocating to study social and ethical implications of nanotechnology, as advocated among others by David Guston in Arizona State University studies of anticipatory governance of nanotechnologies as a way of doing "responsible innovation."<sup>3</sup> All these views provide ways to understand how the science and practice of nanotechnology progressed, and how the actor-networks to perform the work emerged. To be analytically founded, all viewers need grounding in the history of what happened. In my study, I adapt Actor-Network Theory techniques used by Latour to 'follow the actors,' focusing on the entrepreneurial research teams, to see how they worked together to collaboratively co-create the teams to perform the research and produce outputs that are visible today.

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<sup>3</sup> David H Guston, "Understanding 'Anticipatory Governance,'" *Social Studies of Science* 44, no. 2 (April 2014): 218–42, <https://doi.org/10.1177/0306312713508669>.

Instead of seeking the insider reporter, for this analytic study I analyzed artifacts created by ISN members themselves, demonstrating an approach available to any outside viewer in 2019. My key study input documents were the research project descriptions, in changing versions captured over time by the Internet Archive. These project descriptions, along with video recordings of presentations, news articles and web sites, and reports to the MIT President and the Army Research Office research sponsor, constituted my data corpus. In addition to the qualitative analysis regularly performed in STS studies, I used quantitative analytics to understand the research portfolio and social networks of researchers performing ISN basic and applied research. These quantitative analyses provide useful insights about which actors in these emergent networks were more impactful than other actors in the areas studied. Although qualitative analyses did provide richly detailed descriptions, quantitative analysis gave insights to identify high-impact participants, particularly in dynamic networks transiting geographical boundaries. (The data science methodologies I used for quantitative analyses are described in Appendixes A and B.)

## **Introduction to the ISN**

Federal research sponsors share Vannevar Bush's belief that emerging technologies and emerging ventures, large and small, drive growth in the United States. After the Cold War ended, US federal science and technology (S&T) managers sought to redirect federal S&T from a defense focus, to gain broader benefits for the country. Faced with increasing global competition and declining research investments, federal S&T managers and national research leaders alike sought new partnerships to prevent US economic decline. Facing a similar situation at the end of World War II, in 1945 Vannevar

Bush presented the President with “Science – The Endless Frontier” as a blueprint for moving federal S&T from a war footing to provide the nation peacetime economic dividends.<sup>4</sup> Such benefits emerged from defense-funded developments of the Internet and the space program, which spun off S&T-based industries and jobs. STS scholar Daniel Kleinman reviewed Bush’s original proposal, reviving awareness in the 1990s.<sup>5</sup> The US Council on Competitiveness used the proposal to shape their 1996 “Endless Frontier, Limited Resources” recommendation to set post-Cold War priorities for S&T investments.<sup>6</sup> As the 2002 National Research Council advocated in their report “Small Wonders, The Endless Frontier,” sustained investment in nanotechnology could contribute to a federal R&D portfolio to advance materials science and nanotechnology applications, educating workers and reshaping industry, in order to provide lasting economic benefit for the nation.<sup>7</sup>

The National Nanotechnology Initiative (NNI) was formally established in 2000 after years of government-funded nanoscience. The vision for NNI was to coordinate federal research and development (R&D) efforts to accomplish a shared vision of “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.”<sup>8</sup> This initiative focused on the core transition from nanoscience to technology. As described in “Small Wonders, Endless

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<sup>4</sup> Bush, “Science -- The Endless Frontier: A Report to the President.”

<sup>5</sup> Daniel Lee Kleinman, *Politics on the Endless Frontier: Postwar Research Policy in the United States* (Durham: Duke University Press, 1995).

<sup>6</sup> Council on Competitiveness, “Endless Frontier, Limited Resources: U.S. R&D Policy for Competitiveness” (Washington, DC, 1996).

<sup>7</sup> National Research Council (U.S.), ed., *Small Wonders, Endless Frontiers: A Review of the National Nanotechnology Initiative* (Washington, DC: National Academy Press, 2002).

<sup>8</sup> National Nanotechnology Initiative (NNI), “NNI Vision, Goals and Objectives,” 2017, <http://www.nano.gov/about-nni/what/visiongoals>.

Frontiers,” federal coordination of nanoscale research from 1996 on built on decades of nanoscale research in carbon atoms, molecular engineering, polymers, and other small-scale materials discovery and analysis catalyzed in 1959 by Richard Feynman’s lecture at CalTech.<sup>9</sup> Feynman also explored roles for citizen-science, like STS scholars who sought to increase the role of ordinary people in creating scientific knowledge.<sup>10</sup> Since the formal start of the NNI, the US government allocated more than \$24 billion. This significant taxpayer investment incentivized researchers to create innovative new capabilities leveraging nanotechnologies. The people who supported this investment should be able to learn about the results.

As the Army’s contribution to the NNI, in 2000 the US Army Research Office sponsored a university competition to apply nanotechnology to improving human protection. Soldiers were the first customers of technologies anticipated to have widespread commercial uses. The Massachusetts Institute of Technology (MIT) competed against more than fifty universities and won the competition, with a portfolio of university-industry-Army researchers collaborating to create the Institute of Soldier Nanotechnologies (ISN). MIT proposed to establish a center bringing together academics from MIT to conduct research with industry and Army partners. The goal was to create and transition to useful form nanotechnologies to improve human protection, addressing a range of soldier needs from combat operations to normal daily activities. Initial ISN focus areas were “Lightweight, Multifunctional Nanostructured Materials and Fibers... Soldier

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<sup>9</sup> Richard P. Feynman, “There’s Plenty of Room at the Bottom,” *Caltech Engineering and Science* 23, no. 5 (February 1960): 22–36.

<sup>10</sup> Richard Phillips Feynman and Stephen Battersby, “The Meaning of It All: Thoughts of a Citizen Scientist,” *Nature* 394, no. 6689 (1998): 144.

Medicine... and Blast and Ballistic Threat” protection (isnweb.mit.edu). In 2003, the ISN opened under its first 5-year contract with the Army, valued at \$50 million in basic research funds. MIT and industry partners co-invested funding and effort, and the Army provided applied research funds to accelerate transitions. As taxpayers, the American people invested significantly, and deserve to know their investment results. The ISN reports focused on scientific advancements and summaries of activities, but did not focus on the speed of technology transfer, impacts beyond the institute, or institutional advancements. Did innovations in nanotechnology lead to improved human protection? Did new technologies enable the creation of new US industries? What broad social benefits resulted from this major investment? I will walk the reader through case studies which examine these questions.

## Research Approach and Methods

Bruno Latour demonstrated Actor-Network analysis in his historical analysis of Louis Pasteur’s work with anthrax.<sup>11</sup> Similarly, I will follow the actor-networks across the events, products, and partnerships connecting them in four case studies, using the methodology of organizational history. Rather than modern lab studies which follow scientists in daily operations, I assessed the ISN using current publicly available information provided contemporaneously by the ISN to educate the public, partners, fellow researchers, and research sponsors. Influenced by rising citizen-scientist engagement in research, research sponsors implemented NNI outreach goals into the ISN contract to require communications and outreach so that interested viewers could

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<sup>11</sup> Bruno Latour, “Give Me a Laboratory and I Will Raise the World,” *Science Observed* 141 (1983), <http://www.bruno-latour.fr/sites/default/files/12-GIVE-ME-A-LAB-GB.pdf>.

learn the progress of ISN researchers and partners in creating new knowledge and transitioning nanotechnologies to usable forms.

Now, looking back more than a decade at that historical era, data access challenges result from the ephemeral nature of public information-sharing channels. Some information formerly available is no longer accessible: reports, videos, and articles have been re-hosted, put behind Internet paywalls, or removed from web access. My four historical case studies provide insights into different aspects: starting a twenty-first century research institute; linking a social network of people to create basic research; accelerating cancer research with nanotechnology applications; and mobilizing ISN and external partners to address an emergent urgent operational need of soldiers affected by Traumatic Brain Injuries in combat, catalyzed by student prototypes. The ISN's researchers partnered with other academic and government researchers, collaboratively co-creating research focused on simulating and sensing brain injuries. These emergent teams engaged in enrollment and translation, creating capabilities, and adjusted to changing circumstances, which in turn shaped what could be created. The vision was shaped and transformed by actions and events after the original vision was set forth, and impacted by users and non-users of the technologies.

My research provides new knowledge, demonstrating how this community operationalized Latour's concept of translation. I analyzed case studies with STS qualitative and quantitative methodologies in order to evaluate MIT ISN's delivery on their promises. In this study, I describe **what** the ISN did, and explain **how** they did it, as well as how and why the results differed from the original vision. My case studies of actor-

networks in a modern laboratory can also be useful in evaluating other similar federally funded research initiatives.

## Research Design with Case Studies

Researchers have broadly studied nanotechnology's potential impacts on society and the environment. In this effort, I perform a focused analysis of a specific historical example, using STS analytic views on four historical case studies to evaluate the ISN's delivery on the founding director's fulfillment of the NNI vision. Following Latour's methods of historical analysis of French scientist Louis Pasteur's work with anthrax, I research the overarching question of how the initial phase of the Army-funded ISN at MIT, from 2002 through 2007, advanced nanotechnology convergence and delivered nanotechnologies to improve human protection, as advocated by the National Science Foundation.<sup>12</sup> To increase the ability of federal R&D managers to contextualize my research, my case study analysis uses Defense funding structures as frames to focus on different aspects and actor-networks involving the ISN: 6.0 for projects during initiation before formal funding; 6.1 for Basic Research focused on scientific knowledge discovery; 6.2 for Applied Research to align science with relevant applications; and 6.3 for Prototyping for specific solutions.<sup>13</sup>

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<sup>12</sup> National Nanotechnology Initiative (NNI), "NNI Vision, Goals and Objectives."

<sup>13</sup> The Army Research Office (ARO) aligns funding with technology maturity. Basic Research is identified in Defense budget requests as '6.1' funding, focused on producing new knowledge, while Applied Research, identified as '6.2' funding, supports exploratory development for specific military application and technology transition. Advanced Technology Development, identified as '6.3' funding, seeks to demonstrate technology prototypes in realistic operational settings. For the ISN as an entrepreneurial startup venture, funding and efforts before receipt of Army funds were identified as '6.0' funding, and supported development of the proposal which won the ARO contract for the ISN. John D. Moteff, "Defense Research: A Primer on the Department of Defense's Research, Development, Test and Evaluation (RDT&E) Program" (Washington, DC: Congressional Research Service, The Library of Congress, May 5, 1998), [www.dtic.mil/get-tr-doc/pdf?AD=ADA478217](http://www.dtic.mil/get-tr-doc/pdf?AD=ADA478217).

## Co-Creating the Institute

The ISN as an institute was created under the leadership of founding Director Edwin ‘Ned’ Thomas, using enrollment techniques akin to those described by Bruno Latour.<sup>14</sup> The founding director articulated a vision of integrated nanotechnology protecting soldiers in a battlesuit, and recruited researchers, Army partners, and industry to participate. The initial vision was unconstrained: nanotechnologies could provide enhanced protection for soldiers and other humans.<sup>15</sup> However, as I explore in Chapter 3, his vision changed in implementation, responding to controversies, real-world constraints, and opportunities. This ISN vision was shaped by competing ideas: how to study nanotechnology; what applications should be prioritized; how to collaborate; how to respond to controversies and policy constraints; and the practical challenges of creating knowledge and transitioning nanotechnologies to useful form.

The founding era opened a set of framing issues to explore the ISN: enrollment, competition, collaboration for translation, and controversy.

### ***Enrollment***

Professor Thomas formed the team that competed for the ISN contract and established the Institute. To shape their portfolio of problems to move from nanoscale science to transition-ready nanotechnologies to help soldiers, the founding team leveraged insights from Army-hosted workshops and discussions with Army researchers and soldiers, including Army officer graduate students, and visited Army training sites to

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<sup>14</sup> Bruno Latour, *Science in Action: How to Follow Scientists and Engineers through Society* (Cambridge, MA: Harvard Univ. Press, 1987); Latour, “Give Me a Laboratory and I Will Raise the World.”

<sup>15</sup> Edwin L. Thomas, *The Institute for Soldier Nanotechnologies: Taking Nanotechnology from the Laboratory to the Soldier*, MIT World (Cambridge, MA, 2003), <http://techtv.mit.edu/videos/15884-the-institute-for-soldier-nanotechnologies-taking-nanotechnology-from-the-laboratory-to-the-soldier>.

experience real soldier training.<sup>16</sup> Problems to solve came from Army and scientific workshops on Soldier nanotechnology, and Army futures groups identified capability gaps. The ISN ‘team of teams’ emphasized collaboration between academics, industry, and Army research sponsors. Soldiers were both the research target, and collaborative participants as on-site graduate students and applied research partners.

Professor Thomas recruited leaders who committed to collaborate to bring the vision to life. Well-known scientists were the first researchers. These thought leaders partnered across department and disciplinary boundaries.<sup>17</sup> These science leaders were also entrepreneurs who founded businesses in medical applications, consumer electronics, sensors, protective materials, and computer simulations, contributing to MIT’s entrepreneurial ecosystem. These research leaders knew how to work with intellectual property, patents, business agreements, and funding sources. MIT researchers and venture capitalists were enrolled, attracted by the accomplishment track records of early ISN recruits, including MIT Institute Professor Robert Langer: inventor, company founder, and youngest person elected to all three American science academies. Well-known MIT professors joining the ISN included Yoel Fink, Karen Gleason, Michael Cima, and Ian Hunter. Business magazine *Forbes* featured Angela Belcher in a cover story about “The Next Small Thing,” about forecasted impacts of nanotechnology.<sup>18</sup> As an active

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<sup>16</sup> *MIT Infinite History: Waterproof Soldier Nanotechnology*, 2003, <https://infinitehistory.mit.edu/video/waterproof-soldier-nanotechnology>.

<sup>17</sup> William Peters, “What Matters: From Molecular Beams, to Energy, to Helping Soldiers: A Journey of Learning at MIT,” *MIT Infinite Connection*, December 2002, <https://alum.mit.edu/news/WhatMatters/Archive/200212>.

<sup>18</sup> Elizabeth Corcoran, “The Next Small Thing,” *Forbes*, July 23, 2001, <https://www.forbes.com/forbes/2001/0723/096.html>.

enrollment process, science leadership brought business interest to transition technology and market products.

### ***Competition***

Competition for the ISN contract was fierce. This unique research opportunity could be as significant an economic force and change to the world as the Internet had been. Scientists and engineers at MIT already demonstrated early leadership in nanotechnology. An elite institution, MIT ranked among the world's top engineering schools in several surveys, and had experience contributing to national defense by partnering with business. Although specific proposal details were not released to the public, ISN leaders described advantages the founding team and early research partners brought to their successful proposal. MIT offered an entrepreneurial ecosystem with norms suited to support this boundary-spanning institute. MIT professors such as ISN deputy director Tim Swager combined research with consulting to transition their technologies. As a result, awareness of the value of Intellectual property and patents that could show venture capitalists the future value of a business was widespread. MIT's Technology Transfer Office linked community members with patent attorneys and MIT Venture Mentoring alumni. The MIT \$50K Entrepreneurship Competition gained national media coverage of business start-ups gaining venture capital funding through business plan presentations.<sup>19</sup> Many ISN founding researchers had co-founded start-up businesses, so had experience with bringing technologies to the market.

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<sup>19</sup> The MIT entrepreneurship competition has expanded from a \$50,000 prize to a \$100,000 prize, and broadened scope from start-up businesses to socially-aware businesses. MIT Entrepreneurship Center, MIT Sloan School of Business, "MIT \$100K Entrepreneurship Competition," 2010, <https://www.mit100k.org/>.

## ***Collaboration for Translation***

The ISN used competitions to increase collaboration, accelerate transitions, and build community among students, professors, and industry. ISN researchers collaborated across boundaries, to achieve translation of their ideas, inscriptions, student researchers, patents, and products. Student and post-doctoral research and dissertations were overseen by professors from at least two academic departments. International graduate student teams brought together skills in physics and material sciences, computer sciences and medical applications, mathematics and communications, publishing papers that represented seven or more MIT academic departments. The ISN Soldier Design Competition brought in undergraduate teams to solve dual-use problems for soldiers and civilians with practical prototypes in months – no academic credit granted, only prestige and possible prize money. The Army provided challenges and mentors. Student teams could solve a defined challenge, or propose to the ‘open challenge’ category. Teams had to solve problems in a novel way, demonstrating awareness of prior art and ability to submit patents if their team chose to do so. Semifinals included ‘elevator pitch’ briefings like the MIT \$50K Entrepreneurship Competition. Spring finals included judges from industry, MIT and West Point academics, and Army leaders, who assessed prototype demonstrations. Professor Thomas hailed the results: “...student startups and excitement in terms of innovation and creating new technologies to try to solve hard problems.”<sup>20</sup>

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<sup>20</sup> *MIT Infinite History: Innovation at MIT*, Elemental MIT, 2016, <https://infinitehistory.mit.edu/video/innovation-mit>.

## **Controversy**

External controversy came from the outset, when MIT's proposal used the image of the Radix comic book heroine in futuristic battlesuit without permission. Media awareness and critiques from scientific referent groups, including premier journal *Nature*, shaped the implementation of the ISN. Internal controversy also arose around the Soldier Design Competition, designed to engage MIT undergraduates in prototyping material solutions that could be applied to Soldier challenges. Faculty members voiced concerns about research as not focused on human protection writ large, instead becoming too involved with Army warfighting. These competing ideas from different relevant partners shaped the research portfolio, and demonstrated flexibility in interpreting the vision as voiced through a variety of communications.

Controversy also arose from and shaped policies. Policies at MIT and the Army research sponsor caused any projects that could become classified to be eliminated from the portfolio: MIT required all research to be open to all nationalities and publishable. As a result, other universities gained the opportunity to work on these projects, as well as other focus areas proposed in their own responses to the ISN contract competition.

## **Research Questions**

Through my analysis, I describe how this Institute came to be, and what mechanisms ISN leaders used to create a new scientific community through enrollment and translation. What role did competition and collaboration play in bringing nanotechnologies to make a difference for soldiers and society? These mechanisms shaped the ISN's first contract performance: recruiting well-known researchers who brought research projects to fill the ISN research project pipeline; using business

involvement to transition technologies; and pursuing new research and seeking technology transitions. What was done, and how did it work? And how did the implementation change from the initial vision, based on controversies, policies, and constraints? From the detailed fine-grained analysis of what was done for each case study context, I assess what overarching impact the ISN had and how that impact compared with founding team's vision of fulfilling NNI aspirations.

## **6.0 Founding the Institute**

The key leader for the ISN was founding director Professor Edwin 'Ned' Thomas. He enrolled the founding team of academic and industry partners, setting in motion the processes for translation. As I will assess with quantitative research portfolio analysis, his choices can be seen in the research projects which were started, sustained, and stopped. I analyzed enrollment using my quantitative ISN project portfolio analysis in Chapter 3 with analytic methodologies detailed in Appendix B. In addition, I qualitatively assessed publicly accessible reports, videos, and public materials released by the ISN, MIT, the Army and other organizations describing the founding of the ISN as an institute focused on the following overall research questions:

- How were ISN participants - people, firms, and projects – enrolled, qualitatively and as traced through portfolio analysis?
- How did controversy shape the venture, both from external sources and from inside the institute?
- How did competition and collaboration shape the ISN's efforts?

## 6.1 Basic Science and Social Networks of Actors

Pursuing basic science research to advance biotechnology/ nanotechnology convergence, teams of researchers under Professor Angela Belcher grew social networks of actors.<sup>21</sup> As I analyzed in Chapter 4 qualitatively and with quantitative methods detailed in Appendix A, she used enrollment and translation, and her research teams collaboratively co-created novel capabilities and learning structures. Her actions as a well-known researcher and entrepreneur doing core research at the ISN, and exposing her intellectual property through the ISN, encouraged other researchers to collaborate. The Belcher research teams brought together teams of people, technologies, and publications. External researchers cited these works, demonstrating her translations and making her team function as an obligatory point of passage for others working at the nano/bio convergence interface. These networks provide a useful case to evaluate how social networks built around technologies can be assessed for their emerging influence.

Quantitative computational social science techniques for Social Network Analysis enabled me to study the structure of the relationships between people, technologies and publications as actors in an emerging network: the connections between the people who collaborated on Belcher-led research projects, published journal articles, created technologies that transitioned, and worked together in commercial ventures. These quantitative structural analyses assert analytical conclusions about relative importance of specific actors, based on quantitative statistical measures such as betweenness and

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<sup>21</sup> Mark Granovetter, "The Strength of Weak Ties: A Network Theory Revisited," *Sociological Theory* 1 (1983): 201, <https://doi.org/10.2307/202051>; Mark E. J. Newman, Albert-László Barabási, and Duncan J. Watts, eds., *The Structure and Dynamics of Networks*, Princeton Studies in Complexity (Princeton: Princeton University Press, 2006).

centrality, and highlighted previously difficult to discern importance of actors in the network. However, rarely are quantitative analyses of relative importance assessed qualitatively. In this case study, I looked qualitatively at activities of actors in the years in the ISN founding era, and used these activities to validate or refute quantitatively based assertions using social network analysis of these actors. Measures including centrality, closeness, betweenness, and other analytics were used to assess the relationships between these human actors and with their technologies and businesses. These analytics can help analysts overcome the challenges of detecting very early network impactors, in time to invest to reinforce success or identify obstacles to reduce.

This basic research group provides a useful focus for this qualitative and quantitative analysis. Their research is clearly traceable to the ISN, in contrast with the blended funding used for applied research, and so provides a clear baseline for this analysis. Both qualitative and quantitative computational social science techniques for social network analysis will be used to assess the connections between the people who collaborated on Belcher-led research projects, published journal articles, created technologies that transitioned, and worked together in commercial ventures. Outputs of both approaches are compared to see how each approach offers different insights.

Specific research questions include the following:

- How can quantitative social network analysis be used with qualitative analysis to identify early high-impact relationships that led to nanotechnologies for human protection?
- How do results of both analytic approaches compare; can the techniques be used to validate each other; and can results be generalized?

## 6.2 Applied Research for Cancer Research and Science Education

Applied research for cancer research and Science, Technology, Engineering and Math (STEM) education were advanced under ISN Co-founder and Professor Paula Hammond and her research group. Due in part to her ISN leadership, Professor Hammond was selected to lead the MIT Department of Chemical Engineering in 2015, the first woman and first person of color to do so.<sup>22</sup> As described in Chapter 5, she worked collaboratively with fellow ISN Professor Angela Belcher and their research teams to create novel nano-patterned battery materials that self-assembled using viruses which were featured in the peer-reviewed journal *Science*.<sup>23</sup> Professor Hammond's research team focused on nano-/bio-materials in polymers that added drug delivery materials to fight cancer.<sup>24</sup>

Professor Hammond focused on increasing awareness of S&T, which supported Army and federal goals to increase American student interest in Science, Technology, Engineering, and Math (STEM), like goals upheld by Vannevar Bush in *Science – The Endless Frontier*. Her communications over widely accessible channels such as TED Talks and MIT Infinite History interviews translated this learning into action at a distance.<sup>25</sup> These new communications approaches provided exemplars of new approaches to

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<sup>22</sup> Chemical Heritage Foundation, "Women in Chemistry: Paula Hammond," Women in Chemistry, November 17, 2015, <https://www.chemheritage.org/historical-profile/paula-hammond>.

<sup>23</sup> K. T. Nam et al., "Virus-Enabled Synthesis and Assembly of Nanowires for Lithium Ion Battery Electrodes," *Science* 312, no. 5775 (May 12, 2006): 885–88, <https://doi.org/10.1126/science.1122716>.

<sup>24</sup> Peter Dizikes, "Advanced Thin-Film Technique Could Deliver Long-Lasting Medication," *MIT News*, August 4, 2014, <http://news.mit.edu/2014/advanced-thin-film-technique-could-deliver-long-lasting-medication-0804>.

<sup>25</sup> Chris Boebel, *MIT Infinite History Interview with Paula Hammond, MIT '84, PhD '93*, 2011, <https://infinitehistory.mit.edu/video/paula-t-hammond-84-phd-93>; Paula Hammond, *TED Talk: A New Superweapon in the Fight against Cancer*, 2015, [https://www.ted.com/talks/paula\\_hammond\\_a\\_new\\_superweapon\\_in\\_the\\_fight\\_against\\_cancer/](https://www.ted.com/talks/paula_hammond_a_new_superweapon_in_the_fight_against_cancer/).

communicate results of cutting-edge research, shedding light on the ability of the broader public to learn about this research.

These cancer-fighting nanoparticles could fulfill national R&D goals, but also expose issues of who the technologies can help, and how users and non-users shape the technologies. Professor Hammond's research opens questions about who can and who cannot take part in the benefits of this research, and how users and non-users shape technology approaches. She advocated new methods to broaden STEM participation. Her outreach to underserved scientific and education communities extended awareness of nanotechnology to traditionally underrepresented scientific communities, particularly researchers from Historically Black Colleges and Universities (HBCUs).

Professor Hammond demonstrated new mechanisms for sharing access to nanotechnology instruments and described new approaches to collaboration. The ISN teams were able to perform movement from Mode 1 traditional disciplinary science, focused on pure knowledge, to Mode 2 transdisciplinary science, teaming to focus on specific real-world applications.<sup>26</sup> However, Professor Hammond's work with HBCU researchers highlights the challenges of Mode 2 for organizations lacking the kind of sustained strategic partnerships and funding embodied in the ISN-Army relationship. Specific questions include the following:

- How did users shape this technology?
- How can major institutions partner with underrepresented scholars to create new modes to participate in this research?

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<sup>26</sup> Helga Nowotny, Peter Scott, and Michael Gibbons, "Introduction: 'Mode 2' Revisited: The New Production of Knowledge," *Minerva*, Special Issue: Reflections on the New Production of Knowledge, 41, no. 3 (2003): 179–94, <https://doi.org/10.1023/A:1025505528250>.

### 6.3 Prototype Traumatic Brain Injury (TBI) Sensors and Research

As described in Chapter 6, MIT student teams volunteered without course credit to compete in the ISN Soldier Design Competition. Enrolled and motivated by the opportunities to solve meaningful real-world problem, work with Army mentors, and compete for prestige and prize money, the student teams created an entirely unforeseen pipeline of prototype products and start-up companies. From these prototypes came new types of formal relationships with Army innovation sponsors, beyond the initial research partners. New pathways for translation were created by these undergraduate-led teams. Leveraging the student prototype brain sensor, the ISN enabled co-production of TBI sensors and the brain research needed to apply them. More than 170 contributors nationwide converged on the ISN as passage point, to deploy brain sensors and design research about traumatic brain injuries being experienced by soldiers in war in Iraq and Afghanistan. As described in Chapter 6, Professor Raúl Radovitzky and his team modeled how explosive blast impacts led to brain injuries, focusing on the complex environments soldiers faced in concurrent combat operations in Iraq and Afghanistan.<sup>27</sup> The far-flung collaborative teams rapidly expanded enrollment and translation, assessing what could be researched; identifying how new data captured by the brain sensors could shape future research; and iteratively extending the boundaries of science and actionable technologies that could be deployed on soldier helmets. Damaging humans purposefully for research is unethical, so the ISN created multi-scale computer models of brains, skulls, helmets, and protective gear confronted by varying intensities and shapes of blast waves

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<sup>27</sup> Brittany Sauser, "Modeling Brain Blasts," *MIT Technology Review*, November 25, 2008, <https://www.technologyreview.com/s/411248/modeling-brain-blasts/>.

illuminated possible mechanisms of brain injury. These *in silico* models were then compared with soldiers' documented combat injuries to advance scientific understanding of brain injuries, described by Army leaders as "the signature wound of these wars."<sup>28</sup>

The many soldiers who lived through improvised explosive blasts and resulting traumatic brain injuries created a sense of urgency among Army leaders. Having so many wounded soldiers survive with brain injury resulted from a highly efficient medical evacuation system on the battlefield, which enabled wounded soldiers to be treated for injuries that would have been deadly in earlier wars. The paradigm of injury changed to from dying on the battlefield to living long lives with complex injuries. For Army leaders such as General Richard Cody, Vice Chief of Staff of the Army, this created the perceived need to solve this issue urgently. This urgency led him to direct accelerated acquisition, testing, and deployment of brain sensors to soldiers in Iraq and Afghanistan within seven months. This ISN-centered community demonstrated collaboration to accelerate translation, motivated rapidly to deliver technology-focused protection solutions for urgent challenges facing soldiers at war. However, potentially promising outcomes were constrained by Army technology transition policies and preferences for mature technologies, which limited adoption. Long-term outcomes included a large Defense brain trauma research portfolio and translation to use this technology to track brain injuries of National Football League players. I assessed the mechanisms and collaborative approaches that overcame technology insertion challenges to meet urgent needs, and constraints.

I analyzed the work of this large prototyping community following these questions:

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<sup>28</sup> "Intrepid Fallen Heroes Fund," December 2018, [www.fallenheroesfund.org](http://www.fallenheroesfund.org).

- How did student prototype teams enroll Army innovation sponsors, creating an unforecasted pipeline to translate innovations from the ISN into the Army and beyond to broader markets?
- How did the different cultures and competing approaches in credibility between MIT researchers advocating emerging technology, soldiers in the field needing solutions, and the Army acquisition community's preference for mature technology shape and constrain the effectiveness of this technology transfer?

## Positioning and Contribution

In considering the position of my research within the STS field, many researchers have considered the social benefits and potential costs of nanotechnology.<sup>29</sup> This emphasis was designed into the original NNI program by National Science Foundation program managers Mihail Roco and William Bainbridge. Both Roco and Bainbridge advocated for potential benefits of nanotechnologies as the foundation of a next industrial revolution, positioning the United States to be economically competitive in the twenty-first century. In addition to benefits, both program managers wanted to ensure consideration of broader impacts of nanotechnology-driven transformation on the society.<sup>30</sup> Both gave presentations, published volumes, and funded research explicitly focused on the social

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<sup>29</sup> Kamilla Lein Kjølberg and Fern Wickson, eds., *Nano Meets Macro: Social Perspectives on Nanoscale Sciences and Technologies* (Singapore: Pan Stanford Publ, 2010); Ahmed S. Khan, ed., *Nanotechnology: Ethical and Social Implications*, Nano and Energy Series (Boca Raton, FL: Taylor & Francis, 2012); Fritz Allhoff, ed., *Nanoethics: The Ethical and Social Implications of Nanotechnology* (Hoboken, N.J: Wiley-Interscience, 2007).

<sup>30</sup> Mihail C. Roco et al., eds., *Nanotechnology: Societal Implications* (Dordrecht, The Netherlands: Springer, 2007); William Sims Bainbridge et al., eds., *Managing Nano-Bio-Info-Cogno Innovations: Converging Technologies in Society* (Dordrecht, the Netherlands: Springer, 2006).

and ethical implications of nanotechnology on the national competitive posture, environment, and employment landscape. Many ethical and social considerations centered on low-probability, high-potential-impact scenarios, such as the self-replicating ‘grey goo’ created by unconstrained molecular replication scenario described in the book *Engines of Creation*.<sup>31</sup> The consideration of ‘anticipatory governance’ of not-yet-discovered or not-fully-implemented nanotechnologies considers potential outcomes which may never come to pass.<sup>32</sup> The social and ethical considerations explore potential impacts, but many are not grounded in the actual practice of scientists and engineers creating nanotechnologies for specific purposes. Rather than **what if** scenario explorations, I want to examine **what is**, to examine the results of Army investments into MIT and industry partners at the ISN under the first director. Many theoretical approaches could be proposed for establishing a nanotechnology-focused research institute with goals of transitioning nanotechnologies to products that improve human protection: how was this realized in the real world by this group of people at this moment in history?

## Conclusions

Through analysis of these four case studies with qualitative and quantitative analysis based on STS methodologies, my research documents the historical founding of the ISN as a contributor to scientific, economic, and collaborative engagement at the beginning of the twenty-first century. By looking in detail at four case studies, each

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<sup>31</sup> K. Eric Drexler, *Engines of Creation: The Coming Era of Nanotechnology* (New York: Anchor Books, 1990).

<sup>32</sup> Daniel Barben et al., “Anticipatory Governance of Nanotechnology: Foresight, Engagement, and Integration,” in *The Handbook of Science and Technology Studies*, 2008, 979–1000; Guston, “Understanding ‘Anticipatory Governance.’”

focused on a different aspect of the ISN, I seek to provide an overarching assessment of what happened in this major investment; how the ISN fulfilled the NNI vision in the first contract period; and assess what an interested observer looking back to the origins can know now. As an emerging entrepreneurial organization, the ISN showed how researchers came together, enrolled as actors in emergent networks, and operationalized translation of nanotechnologies to different communities of users.

An overlapping set of networks led by key leaders shaped what could be done at this moment in time in nanotechnologies. Professor Edwin 'Ned' Thomas led the founding of the Institute. Professor Angela Belcher seeded the nano/bio-convergence basic research social network. Professor Paula Hammond expanded the cancer-fighting applied research from users to non-users of cancer therapeutics, and pivoted to seek to expand the creators of those nano-biotherapeutics to include under-represented minority scholars. Catalyzed by student prototyping teams from the ISN Soldier Design Competition, Professor Raúl Radovitzky advanced brain-blast computational modeling contributing to understanding of TBI impacts on soldiers and civilians. However, the vision adapted, responding to controversies, policies, and constraints that impacted the journey from vision to implementation. Users and non-users shaped what was researched, and broader social considerations shaped what could be researched and who could participate. Voices within the community, the broader media, and referent social arbiters of research value such as the journal *Nature* shaped the ISN.

The founding team of the ISN sought to function as a venture-driven entrepreneurial start-up business, rewarding people who collaborated extensively and contributed tangible results. Sought-after research partners understood the need to bring

their ideas to improve Soldier protection, and used words and actions that demonstrated how their research teams valued soldiers in their multiple roles as partners, customers, and motivation to do cutting-edge research that could transition to make a difference in the real world. Researchers such as Professor Swager implemented an explosive detector that integrated a scientifically new class of electrically conducting polymer.<sup>33</sup> This excitingly novel material also provided a translatable solution that could be packaged into deployable, life-saving FIDO explosives detectors by ISN small business industry partner ICX-Nomadics. Scientific advancements such as Professor Raúl Radovitzky demonstrated with his computer simulation models of human brains impacted by the kind of blasts produced by Improvised Explosive Devices showed mechanisms for Traumatic Brain Injury. His research galvanized a coalition of ISN-Army-Industry researchers who converged to accelerate deployment of Soldier brain injury detection sensors. Adapting to soldiers' emerging needs and responding faster than the Army S&T enterprise signals a strong return on the ISN investment, resulting in ongoing Army and industry investments. Members of the general public, researchers from competing universities, and federal R&D managers alike can benefit from understanding this research community and its methods to achieve results.

In the end, this analysis provides four illuminating historical case studies involving the ISN actor-networks, as research teams collaboratively co-created research and used enrollment to build out their networks. The teams demonstrate how Latour's concept of translation was operationalized, and how the actors enrolled themselves and their

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<sup>33</sup> Aimée Rose et al., "Sensitivity Gains in Chemosensing by Lasing Action in Organic Polymers," *Nature* 434, no. 7035 (April 14, 2005): 876–79, <https://doi.org/10.1038/nature03438>.

partners into emergent networks. The work created capabilities adopted by other researchers and users, fulfilling early goals of the NNI. The Army Research Office as research sponsor adopted venture approaches to transform their sought-after outputs, substantially refocusing emphasis from just providing academic publications as primary outputs, the standard for National Science Foundation research grants, to technology transfers as primary output, with strong requirements for ongoing outreach. This novel research sponsorship approach led the ISN to entrepreneurially generate new nanotechnologies, opportunities, and some challenges. By engaging continually with scientific and military counterparts, as well as members of the public participating in outreach, a new mode of accountability was demonstrated which did not rely solely on post-hoc historical analysis. However, the variance between the original vision for the ISN and resulting shaping by its controversies influenced the actor-networks and catalyzed the data capture of Internet-based research summaries by the Internet Archive, which endures through the present time – but is not guaranteed to survive as an archive. These STS methodologies and historical case studies will provide federal R&D managers, would-be competing universities, and interested outside viewers an approach to assess similar federally-funded research initiatives. STS researchers, citizen-scientists, data scientists, and other analysts may apply, challenge, test, and try the methodologies I outline, to assess how much these approaches can be generalized to other situations. I look forward to engaging in STS dialogues about the operationalization of translation, and bi-directional enrollment between actors. This bi-directional enrollment suggests dynamics in these modern networks which continue to accelerate, and poses opportunities to extend Actor-Network Theory.

Finally, practitioners of technology transition and those who would join their ranks can read this study from the perspective of a roadmap, how particular actors in these historical case studies left traces of their activities that inform us later. Before the case studies, I will discuss my foundation from STS literature and my data-focused methods.

## Chapter 2. Literature and Methods

### Introduction

The scientists and researchers who established the ISN viewed their nanotechnology research work as spanning science and engineering, creating both products and processes. While performing the interdisciplinary research work, the ISN participants also engaged in establishing a new institute, and created the networks of people, technology artifacts, process knowledge and tacit knowledge needed to meet the goals of the research sponsor. In this chapter, I will focus on STS literature that informs my qualitative analysis, including Actor Network Theory techniques used as social theorist Bruno Latour advocated, to “follow the actors.”<sup>34</sup> As an exemplar of how to study scientists non-concurrently, I followed Latour’s historical study of Louis Pasteur working with anthrax and vaccines in the 1870s. The qualitative analysis provides a rich description of how these researchers established this specific institute and built out their networks of human and non-human entities.

To identify patterns of behavior that can be generalized to other activities, I augmented qualitative techniques with quantitative analytic techniques, including portfolio analysis and computational social science data analytics. As common for data science studies, my quantitative analytics focused on data. Here, a major source of contemporaneous data created by ISN researchers were research project summaries posted on the ISN web site and captured by the Internet Archive, a non-profit digital

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<sup>34</sup> Latour, *Science in Action*, 1987.

library. Other public data provide context and detail for the research summaries, and include reports to the MIT President and Army research sponsors, scientific publications, news articles, and presentations by ISN participants. My focus on public data seeks to understand what data exists to support citizen-scientists and other outside observers.

## **Science and Technology Studies (STS) Literature Context**

Turning from study of individual science and technologies, STS practitioners began to study how scientific knowledge is constructed. STS approaches including Laboratory Studies studied the production of scientific knowledge as a human process shaped by social and cultural factors and practices. An important focus was Actor-Network Theory, led by Bruno Latour, Michel Callon, John Law, and other STS researchers to study knowledge production analytically. Actor-Network Theory advocated 'following the actors,' tracing their actions in detail to understand what spoken and unspoken actions and translations were used to create new knowledge. In close observational studies, STS researchers examined how human and non-human actors combined to create socio-technical artifacts and intangible products including techniques and tacit knowledge. These researchers argued that humans shape technology within a social context; technology does not emerge or diffuse in a technologically deterministic way.

### **Laboratory Studies**

Controversies provide STS researchers with opportunity to 'open the black box' of how scientific knowledge is created, disseminated, and negotiated among and between members of teams. By closely observing scientists in their daily actions and describing the work of scientists to translate knowledge into exportable artifacts, many STS researchers employ ethnographic observation and discourse analysis. As a result, STS

scholars gain understanding of how knowledge is constructed in a social and cultural context. Sociologist Karin Knorr Cetina explored how to bring ethnographic techniques to observe the construction of scientific knowledge in the laboratory in her 1983 work.<sup>35</sup> In her laboratory studies, Knorr Cetina observed that the 'scientific' work being done is dominated by the social, cultural, and organization dynamics in which scientific discoveries are made and scientific knowledge is transmitted.

With Stephen Woolgar, Latour studied how scientists worked together and produced facts, observing laboratory practices in person at the Salk Institute in California.<sup>36</sup> A major study outcome was analysis of the micro-transactions between scientists to translate knowledge to inscriptions such as scientific publications, and the enrollment of other scientists to a specific point of view or textual definition of term. Actor-network analysts re-envisioned science from being a black box to being examinable. John Law recognized how radical this claim is, that "...these networks are composed not only of people, but also of machines, animals, texts, money, architectures – any material."<sup>37</sup> The actor-network approach no longer privileges humans as central figures to study, opening the collective to human and non-human actors networking together. Networks of relationships shape and are shaped by each actor. Extending this concept to include non-human actors in creating knowledge, STS researchers saw that society and science were not uniquely human, but instead were constructed of heterogeneous networks.

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<sup>35</sup> Karin Knorr-Cetina, ed., *Science Observed: Perspectives on the Social Study of Science* (London: Sage, 1983).

<sup>36</sup> Bruno Latour and Stephen Woolgar, *Laboratory Life: The Construction of Scientific Facts* (Princeton, NJ: Princeton University Press, 1979).

<sup>37</sup> John Law, "Notes on the Theory of the Actor-Network: Ordering, Strategy, and Heterogeneity," *Systems Practice* 5, no. 4 (August 1992): 379–93, <https://doi.org/10.1007/BF01059830>.

## Heterogeneous Engineering

As shown in his study of micro-level translations which make up the practice of science, Law's actor-network diagnosis is that science is a process of 'heterogeneous engineering' in which technical, conceptual, social, and textual elements must be fit together by the scientist into heterogeneous products. The scientist must enroll, order, translate, and organize as allies "...heterogeneous bits and pieces – test tubes, reagents, organisms, skilled hands, scanning electron microscopes, radiation monitors, other scientists, articles,... – that would like to make off on their own, are juxtaposed into a patterned network which overcomes their resistance."<sup>38</sup> The ISN founding team needed to conduct all these activities in standing up the institute: building labs; organizing networks of researchers to include instruments, know-how, and carbon nanotubes; and establishing collaborative networks with industry and Army partners in order to start their scientific research activities. The orchestration and negotiations required by scientists define this 'heterogeneous engineering.' Scientists must negotiate with research sponsors on what questions to research, assumptions to validate, and resources to use. Labs must be set up and work performed. Other researchers and technicians must be convinced of how experiments will address which questions, how to define data and terms, and what scale models, in computers or analogous systems, are sufficient surrogates. As Latour observed, "Those who are really doing science are not all at the bench; on the contrary, there are people at the bench because many more are doing the science elsewhere."<sup>39</sup> This expansive view includes research sponsors, who both

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<sup>38</sup> Law, "Notes on the Theory of the Actor-Network," p. 380.

<sup>39</sup> Latour 1987, p. 162.

advocate and program funding; and industry partners, who engineer and scale up manufacturing, as participants in the work of science.

Lab studies showed how decision-makers inside and outside the lab set priorities and permitted access to technical instruments. Funding agencies, bureaucrats, legislators, and industry members all require and give influence to support research. Artifacts include briefings, graphics, geopolitical vignettes, game scenarios linking experiments to outcomes, and other translations from lab to the goals these allies seek. Scientists work hard to compel and convince these actors, translating concepts to align to interests from existing and new allies. Dissenters and competitors must be addressed. Researchers produce data using instruments, and technicians with tacit knowledge of how each experiment was actually conducted must convey their knowledge so scientists can write up results in stylized reports for journals. Unnamed peers must be convinced to approve research reports for publication, for citation by other scientists. The negotiations needed to translate these interests may elevate facts to be treated as a 'black box' which allies can adopt. Instead of truth, the shared use of facts matters:

...Establishment of a scientific or technical object depends not on the inherent usefulness or 'truthfulness' of the result, but on whether one succeeds in building a structure of associations between parties enrolled through mutual definitions that hold up.<sup>40</sup>

Usefulness stabilizes the associations between actors in the network. However, Sheila Jasanoff acknowledges the difference between STS studies and the experiences

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<sup>40</sup> Karin Knorr Cetina, "Laboratory Studies: The Cultural Approach to the Study of Science," in *Handbook of Science and Technology Studies*, ed. Sheila Jasanoff et al. (Thousand Oaks, CA: Sage, 1995), 140–66, <http://dx.doi.org/10.4135/9781412990127.d12>. pp. 159-160.

many scientists live. She notes that the dichotomy between most scientists' experience and the ways some STS researchers explain facts as socially constructed must be overcome:

Scientists and decision-makers, still largely wedded to preconstructivist understandings of science, tend to feel excluded or even patronized by a specialist disciplinary discourse that strikes them as unnecessarily opaque and distant from their lived experience.<sup>41</sup>

While the ISN participants from the founding era may view their science in preconstructivist terms, the STS analysis can illuminate how these efforts are constructed by people collaborating. My analysis sheds light on patterns of technology transition, useful to other research teams bringing technologies to military and commercial users.

### **Historical Study of Pasteur**

Latour studied the heterogeneous engineering of elements and allies with his historical analyses of Louis Pasteur's research on anthrax. Latour extended the laboratory studies from the lab to the field and back, and backwards in time. His hundred-year retrospective history studied science as practiced in the 1870s by French researcher Louis Pasteur in developing and disseminating knowledge of anthrax and vaccination. In this historic example, micro- and macro-actors can be understood in context of each other, and key knowledge practices such as translation, inscription, and transmission can be studied to understand science in action. Latour looked for associations between actors, and viewed controversies as windows into the actual practices. The controversies

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<sup>41</sup> Sheila Jasanoff, "STS and Public Policy: Getting Beyond Deconstruction," *Science, Technology and Society* 4 (1999): p. 63.

illuminate how actors build their identity as individuals and groups, including non-human entities; how actions may diverge from initial goals; how closure may be deferred by interactions between objects and agencies; how facts link existing to new knowledge and actors; and how to study the social interactions.<sup>42</sup> Pasteur's research showed the impact of scaling up from invisible microbes to a disease affecting farm animals and French citizens. French statisticians created models of health impacts on people of the disease caused by anthrax microbes. Translations between contexts were debated and repeatedly negotiated, in person and through inscriptions including texts, presentations, and graphic images. Latour outlines the mechanisms of stabilizing facts, showing how scientists enroll and control allies, minimizing dissent.<sup>43</sup> Opportunistic connections with allies can be exploited by scientists like Pasteur, who enrolled partners working at external laboratories to work with the anthrax microbes he purified and produced in scaled-up quantities. Latour summarizes the heterogeneous engineering challenge:

The problem of the builder of the 'fact' is the same as that of the builder of 'objects': how to convince others, how to control their behavior, how to gather sufficient resources in one place, how to have the claim or the object spread out in time and space....<sup>44</sup>

This 'action at a distance' spreads knowledge and technologies through the artifacts created by the actor-networks working together. The research actors need to enroll others to extend work created in the laboratory into practical uses.

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<sup>42</sup> Bruno Latour, *Reassembling the Social: An Introduction to Actor-Network-Theory (Clarendon Lectures in Management Studies)* (New York: Oxford, 2005).

<sup>43</sup> Latour, *Science in Action*, 1987.

<sup>44</sup> Latour 1987, p. 131.

## Key Terms Defined

In *Reassembling the Social*, Latour includes as objects of study “any type of aggregate from chemical bonds to legal ties, from atomic forces to corporate bodies, from physiological to political assemblies.”<sup>45</sup> With the Internet, this experience of actors networking via web and real life is common. Latour acknowledged this networked set of identities which individuals encompass: “...Philosophers have been carried out by the verb **to be** and its problem of identity and not by the verb **to have**.... But the web is changing all of that...: ‘to have’ (friends, relations, profiles) is ... a stronger definition of oneself than ‘to be’.”<sup>46</sup>

The actor-networks self-assemble into a variety of networks, some overlapping in membership. For my study, the Internet is not the network of interest. For ISN researchers, the Internet is a channel of communication used by human actors to enroll, communicate, and persuade other actors to invest in and acknowledge their knowledge artifacts. ISN cases will be used to test Latour’s theories of the actor-network for applicability in a modern lab context.

## Actors and Networks Defined

As Latour advocated in *Science in Action*, my study seeks to look not at ready-made science, after encased in a ‘black box’ of a textbook, but rather at “...science in the making,” in the process tracing actors as they organize and enroll others to invest in or

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<sup>45</sup> Latour, *Reassembling the Social: An Introduction to Actor-Network-Theory (Clarendon Lectures in Management Studies)*.

<sup>46</sup> Bruno Latour, “Network Theory | Networks, Societies, Spheres: Reflections of an Actor-Network Theorist,” *International Journal of Communication* 5 (2011): p. 6.

follow their program.<sup>47</sup> For Latour, an actor is defined in relation to other actors: “An actor is what is made to act by many others. An ‘actor’ in the hyphenated expression actor-network is not the source of an action but the moving target of a vast array of entities swarming toward it.”<sup>48</sup> In this definition, the variable and contingent relationships between fact-builders define the networks and the heterogeneous actors, which can include human and non-human entities working to align interests and achieve goals.

Among ISN research teams, the bacteriophage viruses which Professor Belcher’s team enrolls to create organic-inorganic compounds for batteries provide examples of non-human actors with agency. Other non-human influences on the network include specialized nano-instruments and processes such as anonymous peer review of articles for publication in scientific journals. Definition of which actors are included in the network involves continuous struggle: “...who includes and who is included, who localizes and who is localized is not a cognitive or a cultural difference, but the result of a constant fight...”<sup>49</sup>

The network is actively embodied and performed by the actors which compose the network at that moment. Associations through enrollment to focus on interests stabilize the network. “The word network indicates that resources are concentrated in a few places – the knots and the nodes – which are connected with one another – the links and the mesh: these connections transform the scattered resources into a net that may seem to

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<sup>47</sup> Bruno Latour, *Science in Action: How to Follow Scientists and Engineers through Society* (Cambridge, MA: Harvard Univ. Press, 1987), 4.

<sup>48</sup> Bruno Latour, *Reassembling the Social: An Introduction to Actor-Network-Theory*, Clarendon Lectures in Management Studies (Oxford: Oxford University Press, 2005), 46.

<sup>49</sup> Latour, *Science in Action*, 1987, 229.

extend everywhere.”<sup>50</sup> The actor-networks exist to achieve action at a distance, using enrollment to bring in new participants and align to shared interests.

### **Translation in the Network**

Latour’s concept of translation emphasized the active work actors do to extend their work and knowledge with others. Translation does not merely ‘diffuse’ knowledge; actors add to, reshape, and deform the knowledge in translation. The essential move is to translate knowledge into inscriptions to enable ‘action at a distance.’ My research shows how translation was operationalized, as ISN actor-networks engaged in a variety of tactics to make translations work in the world. The early technologies emerging from the ISN, including the FIDO explosives detector and the student-team-built prototypes from the Soldier Design Competition, carried the knowledge used to create them within the technology inscriptions. These translations demonstrate Latour’s concept of “tying up with new unexpected allies,” as they enrolled new partners for manufacturing technologies.<sup>51</sup> The teams also demonstrated the tactic Latour described of “inventing new users:” filling an unmet need by collaborating with soldiers in the field to translate a portable lifting device into a system that could be used to lift injured people into medical evacuation helicopters.<sup>52</sup> No prior solution worked to rapidly lift injured people without pre-outfitting the helicopters; the new device enabled the creation of new users. Like the small businesses competing with and being bested by Bell Laboratories, HBCUs described in Chapter 5 are in the position that “without building the expensive laboratories they could

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<sup>50</sup> Latour, 180.

<sup>51</sup> Latour, 125.

<sup>52</sup> Latour, 115.

not afford in an attempt to attract physics or electrons back into their own camp.”<sup>53</sup> As scientific outsiders, the HBCU researchers could not credibly resist, comment on, or build on the new science. Professor Hammond’s outreach with HBCUs enrolls them and translates those researchers from outsiders to nanotechnology research participants, able to contribute and translate their knowledge.

The ISN researchers understood the value of creating a patent as an incontrovertible black box that can be used as an entity, and used to bolster an affiliation with investors and scientific partners.<sup>54</sup> In the case study focused on 6.1 research actor-networks, a patent map visually shows the intellectual property landscape, and shows other entities acknowledging the lineage of their ideas back to inventions patented by Professor Belcher. These acknowledgements of translation demonstrate an example of what Latour describes as “winning trials of attribution.”<sup>55</sup> In order to participate, would-be nanotechnology researchers may view the ISN center and individuals within as a ‘Mecca’ for nanotechnology research, as requested in the original Army contract. Finally, the emergence of the ISN research focused on blast-related traumatic brain injuries from the student team at the Soldier Design Competition demonstrated the tactic of “inventing new goals.”<sup>56</sup> Detecting and characterizing brain injuries received by soldiers in combat operations around the globe in Iraq and Afghanistan were not on the initial ISN research agenda. The perceived urgent need, combined with the availability of networks of researchers focused on soldier protection needs, created an unforeseen opportunity to

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<sup>53</sup> Latour, 127.

<sup>54</sup> Latour, 127.

<sup>55</sup> Latour, 118.

<sup>56</sup> Latour, 114.

address brain injuries. The ISN served as a point of passage, enrolling more than 160 researchers rapidly as allies to develop strategies to detect and resolve brain injuries. The translation continued, as ISN research teams led by Professor Radovitzky recast computational models of potential soldier injuries from bullets into multi-scale models to simulate blast waves from explosives interacting with simulated soldier bodies and brains *in silico*.

## STS Studies of Nanotechnology Issues

As part of the late 1990s NNI (NNI), the National Research Council studied the many potential impacts of federal nanotechnology investments, including economics, manufacturing, education, health and safety. Nanoscience in various forms and disciplines had been conducted over decades, accelerating after physicist Richard Feynman's vision-making speech in 1959 set new challenges to design tiny molecular machines and new materials using carbon nanotubes.<sup>57</sup> The NNI advanced investments in translating nanoscience to nanotechnologies. The National Science Foundation NNI project leaders focused on funding the science and engineering needed to translate nanotechnology to tangible capabilities.<sup>58</sup> As a close follow-on, NNI also sponsored studies of the social-cultural impacts as nanotechnology convergences with information, biology, and cognitive sciences.<sup>59</sup>

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<sup>57</sup> Feynman, "There's Plenty of Room at the Bottom."

<sup>58</sup> William Sims Bainbridge et al., eds., *Managing Nano-Bio-Info-Cogno Innovations: Converging Technologies in Society* (Dordrecht, the Netherlands: Springer, 2006).

<sup>59</sup> Mihail C. Roco et al., eds., *Nanotechnology: Societal Implications* (Dordrecht, The Netherlands: Springer, 2007).

## Nanotechnology Impacts in Society

As studied by a scientific peer review panel in the 2002 NRC report “Small Wonders, Endless Frontiers – Review of the National Nanotechnology Initiative,” a key corollary avenue of investigation was the issue, “Does NNI give sufficient consideration to the societal impact of advances in nanotechnology?”<sup>60</sup> Under the auspices of early National Science Foundation programs examining nanotechnology impacts on society, a number of STS researchers including David Guston, Director of the Center for Nanotechnology in Society at Arizona State University, examined potential social-cultural impacts of nanotechnology. These meta-analyses assessed nanotechnology impacts, rather than nanotechnology in practice.

According to Guston, anticipatory governance arose from the lessons learned from genomics and confronts the core dilemma: “how can technologies be self-consciously governed when, in the laboratory, they are too inchoate but, once in the market, too interwoven with economic and social interests?”<sup>61</sup> Timing is a challenge: starting too early could miss the feasible ways that nanotechnologies could be implemented, but starting too late could miss the ability to shape nanotechnology applications. These researchers sought to forecast potential nanotechnology, often using scenarios, and then to understand what potential impacts might be for various members of a community. Studies of anticipatory governance sought to avoid issues similar to those resulting from secret research in World War II that created atomic weapons with unprecedented ability to

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<sup>60</sup> National Research Council (U.S.), ed., *Small Wonders, Endless Frontiers: A Review of the National Nanotechnology Initiative* (Washington, DC: National Academy Press, 2002).

<sup>61</sup> Guston, “Understanding ‘Anticipatory Governance,’” 226.

change human life. A current example of the category of high-impact technology which can have long-term unforecastable results is human genetic engineering. A change to the human germline could change the genetics of the individual treated, as well as descendants reproduced by that individual. The anticipatory governance frameworks seek to establish ethical and governance frameworks to shape the development of technologies before they already exist, and direct them into paths which are more beneficial for more people.<sup>62</sup> Other studies examined potential ethical implications, including consideration of people who could be impacted by the nanotechnologies but may have insufficient understanding of science to provide informed consent or even guidance of how nanotechnologies should be implemented.<sup>63</sup> Still other social studies of nanotechnologies sought to consider a range of potential social impacts of nanotechnologies, opening up consideration of social justice on underrepresented community members.<sup>64</sup> During the early period of nanotechnology anticipatory governance that overlapped with the founding period of the ISN, asynchronous activities lacked connection with the underlying science and a delay in output produced by the anticipatory governance efforts can cause these well-intended efforts to miss the opportunity to influence the development and deployment of nanotechnologies in society.

### **Challenges in Understanding the Science**

This challenge of lack of visibility into research by outsiders affects not only historical viewers, but also concurrent partners trying to assess the research like the STS

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<sup>62</sup> Daniel Barben et al., “Anticipatory Governance of Nanotechnology: Foresight, Engagement, and Integration,” in *The Handbook of Science and Technology Studies*, 2008, 979–1000.

<sup>63</sup> Allhoff, *Nanoethics*.

<sup>64</sup> Khan, *Nanotechnology*.

researchers advancing anticipatory governance. In basic research, the output can have applications in a wide array of fields and products. When is the material 'done'? Traditional methods used to assess completeness of a technology, such as Defense Technology Readiness Levels (TRL), do not apply. Traditionally, the highest practical TRL 7, represents a complete system such as an airplane which can safely fly and carry passengers. To extend the analogy, the TRL 4 prototype aircraft should only be flown by experienced test pilots to assess the flight characteristics. A TRL 5 aircraft is ready to be fitted out with related components to understand integration challenges and interoperability, ready to integrate pilots with normal levels of skill and training. A TRL 3 or 2 aircraft represents a non-human-flying model used to understand core physics. Program managers and designers traditionally seek to mature technologies from TRL 3 up to TRL 7, to transition mature and producible technology.

This practical approach to assessing technology in terms of system-level transition readiness does not help assess nanomaterials. The same nanomaterial can be used by itself, as a coating or end item, as seen in virus-based batteries, at TRL 7 for some size scale. The nanomaterial may also require integration and testing to be used as part of an end item, adjudged to be at TRL 5. An example of this degree of capability was the organic/inorganic compound used in flexible displays, which required five years to mature for commercialization. The same nanomaterial in a beaker could be foundational for other nanomaterials, either as a product or as a process (virus-based rapid materials evolution or layer-by-layer soft lithography). Since direct results take time and can have broad effects, creating the capacity for further innovation matters.

The capacity to understand and translate nanotechnologies to help community members shape future research is much needed. Organizations such as NASA work with the National Research Council (NRC) to increase community capacity to participate in governing emerging technologies. As described in their Nanotechnology Roadmap, NASA partners with the NRC.

Through an open process of community engagement, the NRC will gather input, integrate it within the Space Technology Roadmap and provide NASA with recommendations on potential future technology investments. Because it is difficult to predict the wide range of future advances possible in these areas, NASA plans updates to its integrated technology roadmap on a regular basis.<sup>65</sup>

These partnerships between scientific fact-builders and the broader social science community to grow both community awareness and create opportunities for community engagement in the governance of emerging technologies is both worthwhile and challenging. Providing those responses back to the local communities in an understandable manner, timely enough to inform and influence the researchers working on nanotechnologies, presents a parallel challenge which has yet to be solved.

### **Why Add Quantitative Analysis**

STS lab studies traditionally focused on qualitative techniques including ethnography. The qualitative techniques provide richly detailed specifics of given

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<sup>65</sup> Michael A. Meador et al., "NASA Draft Nanotechnology Roadmap: Technology Area 10" (Washington, DC: National Aeronautics and Space Administration, November 2010), [https://www.nasa.gov/pdf/501325main\\_TA10-Nanotech-DRAFT-Nov2010-A.pdf](https://www.nasa.gov/pdf/501325main_TA10-Nanotech-DRAFT-Nov2010-A.pdf).

technology case studies. As a supplement to qualitative analysis, quantitative analysis can make visible certain patterns which otherwise would be buried in the data. Through my study, I used both qualitative and quantitative analysis to identify patterns used in transitioning technologies from the lab to market or field. The quantitative approach revealed relationships what would not otherwise be visible because of the size and complexity of the data, and because of the mobility of the community members. Other researchers or research sponsors can use these methodologies to look for similar patterns in broader sets of technology activities.

### Transition-Focused Quantitative Analysis

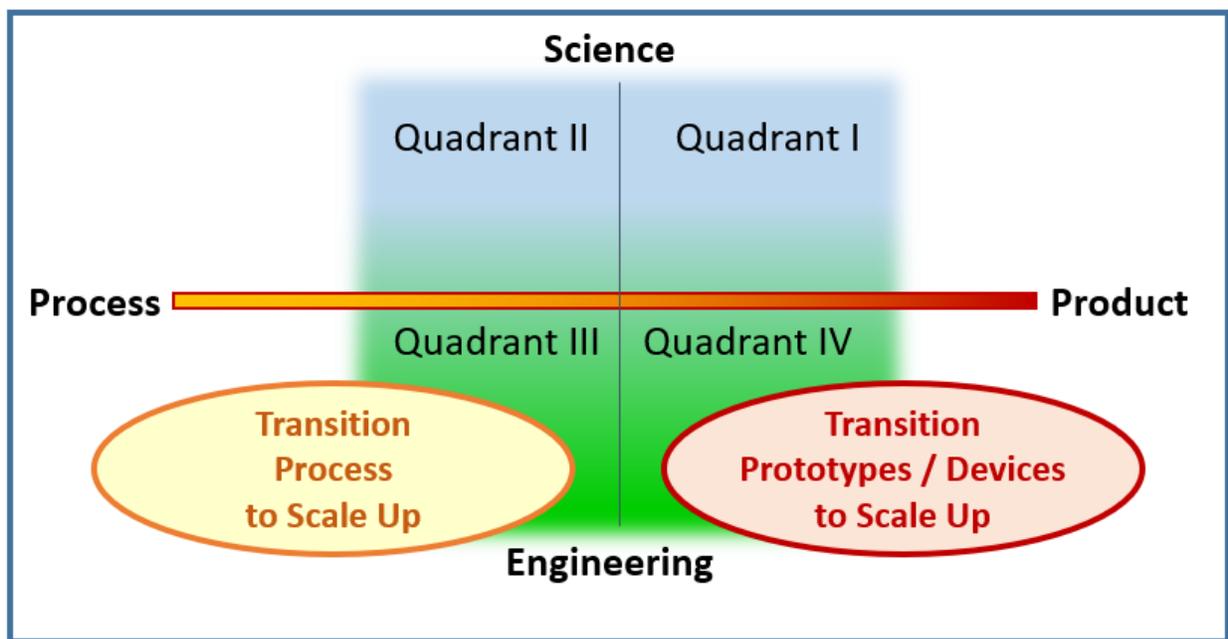


Figure 1. Transition-focused Research Team Analytic Framework (Cartesian Grid)

The ISN contract focused on output in the form of processes and products, particularly prototypes and devices; trained nanotechnologists; knowledge shared in publications; and outreach to partners and the public. As will be discussed in greater detail in Chapter 3, the Cartesian grid system above enables the analyst to characterize

research projects from onset through maturity, measured in terms of technology transition readiness. The axes run from process to product, and maturing from science to engineering. Characteristics of successful teams who started in quadrant I, science focused on a product or capability, can be seen as the team transitions their research through the quadrants in an ordered sequence (quadrants I-IV), or as the team members opportunistically created ways to accelerate transitions into technologies. The entrepreneurial processes that these project teams used can inform other transition-focused research teams to find ways in which gain feedback from potential users. The teams I analyzed found different paths to transition, instead of feeling constrained by the approach from science to engineering as described by ISN professors: researchers practicing basic science seek to develop a capability, then transition that product or capability into a process which can be scaled up. Once scale-up is achieved, researchers would apply engineering techniques to integrate the capability into some type of prototype. At this phase of technology maturity, conventionally the creator team would market that prototype to industry partners or the research sponsor agency, to be scaled into products incorporating those processed materials. Finally, engineers integrate these scaled-up materials into products which can be assessed by users. This sequential process does not allow opportunities for integration of user feedback; the user voice may not be heard.

Transition-focused research teams often describe their progress as pursuing the steps in sequence, moving from pure science to product by way of process engineering. The ISN emphasis on accelerating technologies to transition led the 55 project teams to employ entrepreneurial approaches to accelerate transitions. The patterns of

collaboration worked to accelerate transition of ideas into practice. These approaches to accelerate from science to engineering, in either product or process, can be repeatable. Other research teams learned how to reach out to industry scientists, Army scientists, and Army engineers, to create opportunities to accelerate technology transitions. The host agency also created new opportunities to accelerate technology transition, such as providing an on-site technology transfer specialist skilled in integrating emerging technologies into Army systems. The inclusion of many MIT professors who were skilled at creating products that they could market as the basis of an entrepreneurial start-up company, and also creating products which could be patented and transitioned through licensing, added depth to the ISN.

### **Quantitative Analytic Methods**

The interdisciplinary network science, data science, and computational social science researchers bring quantitative techniques which complement the qualitative techniques often used by STS researchers. Among these quantitative techniques I will use both social network analysis and portfolio analysis. Qualitative descriptions provide rich details that uniquely identify a particular environment and circumstance. I seek to demonstrate that a complementary quantitative analysis can illuminate underlying patterns of behavior that can be common across particulars of domain or group membership. Both analytic approaches add value and understanding to my analysis of a new institute focused on nanotechnology at the start of the twenty-first century. The data science techniques I used for quantitative analysis are informed by emerging work in quantitatively analyzing heterogeneous network structures and the dynamics which can be observed in many networks. Tools used to analyze the networks established by ISN

participants include social network analysis.<sup>66</sup> As described in the journal *Science*, computational social science techniques facilitate analysis by abstracting from specific structures and detailed dynamics within and between networks.<sup>67</sup> As a complement to the richly detailed description from qualitative analysis, quantitative analysis helps identify patterns of self-organization of networks which can be extended and potentially replicated in other settings. To demonstrate this analytic technique, my quantitative social network analysis methodology is detailed in Appendix A, describing the analysis of basic research networks seen in Chapter 4.

My technology portfolio analysis approach is derived as an extension of techniques taught at MIT by Professor Rebecca Henderson, archived online in MIT's OpenCourseWare archive.<sup>68</sup> This quantitative portfolio analysis evaluates a beginning and ending position for each project in the Cartesian grid, between science and engineering, and process and product, in order to identify trajectories toward or away from technology transition. The portfolio analysis methodology is detailed in Appendix B, which provides the basis for my analysis of the founding of the research institute described in Chapter 3. The purpose of my quantitative analysis is to complement the specifics of the qualitative historical descriptions by identifying the patterns of behavior used by the ISN research teams to organize their activities. These underlying patterns can be extended to other teams, research focus areas, and organizations. STS researchers would identify this type of analytic practice as 'technique.' These techniques are commonly used for

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<sup>66</sup> Newman, Barabási, and Watts, *The Structure and Dynamics of Networks*.

<sup>67</sup> D. Lazer et al., "Life in the Network: The Coming Age of Computational Social Science," *Science* 323, no. 5915 (February 6, 2009): 721–23, <https://doi.org/10.1126/science.1167742>.

<sup>68</sup> Rebecca Henderson, "Technology Strategy: MIT OpenCourseWare," Spring 2005, <http://hdl.handle.net/1721.1/56570>.

investment analysis by research funders, potential industry transition partners, and venture capitalists seeking to understand potential returns on their investments. For research teams, understanding how recipients of their technology assess the future prospects of that technology can help inform and shape actions now to enhance likelihood of success in technology transfer.

Latour demonstrated an effective historical way to 'follow the actors' through time in his study of French scientist Louis Pasteur working with partners in laboratory and farmers' fields to study anthrax a century ago. First-person observation is not feasible for analysts looking back at a historical case study. For me, following the actors required interpreting their traces in artifacts: studying the literature, reports, and media descriptions published by members of the ISN in the early 2000s. For this founding era, I used as core artifacts the ISN researchers' own descriptions of each research project and the accomplishments they published for fellow scientists, potential technology transition partners, interested readers, research sponsors, and the broader public. These project descriptions were updated periodically. During the first contract period from 2002 through 2007, the ISN issued new research project descriptions at least yearly. These project descriptions were captured by the Internet Archive ([archive.org](http://archive.org)), a nonprofit digital library. Those Internet-hosted archives can be viewed freely by anyone who seeks to analyze changes between the versions of digital products that were captured.

By analyzing changes between the versions of research descriptions created by the researchers, I identified patterns of team activity which resulted in observable technology transitions. Quantitative analysis techniques enabled me to identify patterns which advanced technology transition and compare them more broadly to other research

projects, across research disciplines. However, this technique is necessarily limited to the evidence available. The authors of the digital artifacts may not be identified, so cannot be interviewed. Co-occurring collaborative or contradicting evidence may not exist, or may not be released to the public. The documents described successes and aspirations, not failures and re-directions. Some re-directions can be inferred from changes in the descriptions, and illustrate how technology-focused research teams follow winding paths. However, even with these constraints, my analysis of transition-focused technology research teams does display patterns of organization which may be useful for federal technology research sponsors, other university research centers, and individual research teams to understand the many ways technology transitions were accelerated in the first five-year contract era of the ISN.

### **Description of the Dataset Captured by the Internet Archive**

Two decades after the activities I study, one challenge was in gaining access to contemporaneous descriptive data created by ISN participants. Memories fade, and actions can be re-interpreted in the light of later events. The Internet Archive provided an open accessible archive of snapshots of ISN web postings, with changes captured over time. The Internet Archive was started in San Francisco, California, in 1996 by computer scientist Brewster Kahle, who established a non-profit digital library under the US Internal Revenue tax code category 501(c)(3). His goal was "...archiving the Internet itself, a medium that was just beginning to grow in use. Like newspapers, the content published on the web was ephemeral - but unlike newspapers, no one was saving it."<sup>69</sup> Starting in

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<sup>69</sup> Greg R. Notess, "The Wayback Machine," *Online: The Leading Magazine for Information Professionals*, October 3, 2002,

2002, the Internet Archive's Wayback Machine web portal enabled external viewers to see the 100 terabytes of web page data that the Internet Archive had captured from the Internet starting in 1996. In comparison, by January 2019, the Internet Archive held images from 339 billion web pages from the Internet, as well as other documents, television shows, and recorded events totaling more than 60 petabytes of data. The anticipated audience includes historians, researchers, and the general public:

Historical researchers can now view significant portions of the Web as it existed at various times from 1996 to the present.... Sources lost because of complex URL shifting can be found by their old URL.... The researcher who is trying to track down the online resources from the bibliography of a four-year-old paper can find them in the archive, even if they have otherwise vanished from the current Web.<sup>70</sup>

The Internet Archive used a combination of manually-triggered and robotic software automation techniques to capture web pages that had been entered into its list of sites to record. However, web page owners who entered specific computer commands as metadata into the web page header information could choose to exclude their pages from automated software robots that periodically crawled the web to perform those data captures.

It is unclear now looking back at the start of the 21st-century exactly why the ISN pages were captured in the Internet Archive. The organization could have requested the service to document information changes, or the Internet Archive might have captured

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<https://web.archive.org/web/20021003191240/http://www.infoday.com:80/Online/mar02/OnTheNet.htm>  
archive of <http://www.infoday.com:80/Online/mar02/OnTheNet.htm> dated 3 October 2002.

<sup>70</sup> Notess.

them after a controversy which shaped the formation of the ISN, discussed in the next chapter. Regardless of the reason, the reality is that Internet Archive captured one or more images for most project pages each year during the first five-year ISN contract. Data gaps are noted in Appendix B.

The core primary documents I analyzed are ISN research description summaries. These templated documents published on the ISN website described various projects across the research portfolio. More than 55 projects spanning seven research focus teams were reported starting in 2002. The Internet Archive captured these web-published documents each year, and more frequently for some projects. (These documents are analyzed as a research portfolio in Appendix B.) Changes can be identified between one observation and the next. Project summary information was augmented by publications by ISN researchers, MIT News Office and other news articles, related Army reports, video recorded presentations, and annual reports submitted to MIT President each June by the ISN Director.<sup>71</sup>

The project summaries and other documents created by ISN participants reflect their own language and conceptual structures. STS theorists might characterize the activities at the ISN differently, viewing the social-cultural-technical activities reflexively and from a constructivist perspective. In contrast, MIT scientists and technologists understood their practice as dividing activities along a continuum from science and engineering, aligned to create either products or processes. While conducting research, team members sought to establish networks within and among the participating research

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<sup>71</sup> Edwin L. Thomas, "MIT Reports to the President 2004–2005: Institute for Soldier Nanotechnologies" (Cambridge, MA, June 2005), <http://web.mit.edu/annualreports/pres05/03.08.pdf>.

teams. ISN team members enrolled research partners in industry and the Army, engaged with scientific peers, and networked with non-participants, including MIT undergraduates, visitors, US Military Academy cadets and professors from West Point, and members of the public.

### **Data Description of Project Summaries Captured by the Internet Archive**

The Internet Archive captured snapshots over time of the ISN project summary webpages. These documents were in addition to the Defense Technical Information Center ([www.dtic.mil](http://www.dtic.mil)) formal program archives. A journalist could have requested the archiving service, to be able to track changes based on importance of the center. The archive may have had a process for capturing high-visibility webpages; responding to the ISN controversy about intellectual property discussed in the next chapter.

Regardless of cause, readers today have a historical archive of ISN research artifacts. Each captured webpage documents research project data. This templated description includes the ISN research team, project number, description, objective, approach, accomplishments, personnel, and a graphic. The Internet Archive meta-data about the captured webpages include capture date, but not webpage creation date, or creator, or approver. Not all desired information remains – but data exists to shed light on this emerging institute’s start-up phase and actor-networks.

## Reading the Data in Detail

https://web.archive.org/web/20040823122113/http://web.mit.edu:80/isn/research/team03/project03\_06.html

INSTITUTE FOR SOLDIER NANOTECHNOLOGIES Enhancing Soldier Survivability 2004

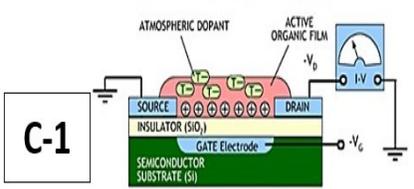
RESEARCH / Team 03

**A** **Project 3.6: High sensitivity sensing based on conducting and semiconducting organic molecules and polymers**

This document presents a summary of Team 3's objectives and approaches as it works on Project 3.6, developing protective measures that will enable the future soldier respond to chemical and biological threats. In addition, this document summarizes the project's accomplishments thus far.

**Objective**  
The primary goals of Project 3.6 are the following:

- Demonstrate use of semiconducting organic materials as ultrasensitive sensing technologies
- Develop platform optical and electronic technologies for future detection schemes
- Develop sensing technology for nitric oxide for use by soldiers

**C-1** 

**Transduction of the chemical response to an amplified electrical signal via transistor action**

**Approach**  
To meet Project 3.6's objectives, researchers use the following approaches:

- Develop approaches to produce, chemically sensitive, active organic semiconductors
- Design materials with specific work function for optimized charge injection at contacts
- Design field effect transistor (FET) structures for chemical sensing
- Characterization: Electrical and Optical

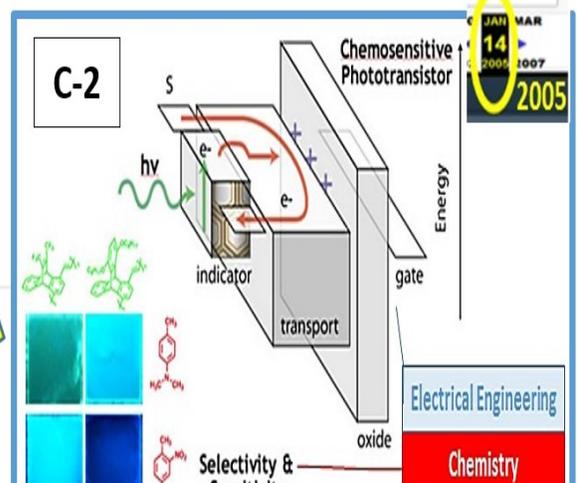
**Accomplishments**  
Team 3 researchers have met the following goals thus far:

- Synthesis of luminescent semiconductive polymers that do not bleach and are suitable for FET sensor applications
- Demonstration of sensor response to indole with high work-function polymers
- Synthesis of a family of nitric oxide sensory materials for optimization
- Electric field modulation of luminescence
- Method for fabricating FET device structure
- Design of Photosensitive FETs

**Electrical Engineering**  
**Chemistry**

**B** **Personnel**  
Principal Investigators  
Prof. Vladimir Bulovic  
Prof. Timothy M. Swager

In addition, one MIT student and two postdoctorate scientists are working on this project.

**C-2** 

**Chemosensitive Phototransistor**

**Electrical Engineering**  
**Chemistry**

**Approach**  
To meet Project 3.6's objectives, researchers use the following approaches:

- Develop methods of nanowire production
- Design materials with specific work functions for charge injection and exciton dissociation
- FET structures for chemical sensors

**Accomplishments**  
Team 3 researchers have met the following goals thus far:

- Developed polymers capable of detecting proteins
- Synthesized polymers containing transition metal sensors for resistivity-based gas sensing
- Developed new fluorescence-based detection methods for nitric oxide
- Demonstrated photoresponse in a novel photodetecting FET structure

14 JAN MAR 2005 2007

Figure 2. Reading ISN Research Summaries from the Internet Archive, comparing 23 August 2004 version with 14 January 2005 version (see Fair Use determination).

Each ISN research project summary gives the overarching project name, describing both technology and the goal. For example, [A] Project 3.6 is titled 'High sensitivity sensing based on conducting and semi-conducting organic molecules and polymers.' Readers who understand chemistry can read this project as integrating both conducting and semi-conducting materials, suggesting controllable flows for electricity. The project refers to high sensitivity sensing, useful for sensors to detect low-availability

particles in the atmosphere. This implies use in military sensors to detect environmental toxins or other substances of concern. By calling out both molecules and polymers, the title suggests scalable chemical approaches to make novel materials with desired properties. The title's three characteristics, high sensitivity, conducting/semi-conducting, and molecules/polymers, suggest materials tunability.

Personnel [B] lists primary investigators Professors Bulović from Electrical Engineering and Swager from Chemistry – demonstrating multi-disciplinary partnering. Personnel describes 'one MIT student and two post doctorate associates are working on the project.' When proposed, months before projects are approved, student research participants may not be known. Primary investigators list the resource level requested for funding, and are responsible for staffing the project with people capable of achieving the goals set.

The graphic [C-1] extends the expectation of interdisciplinary collaboration applying nanotechnology to improve human protection. This project page captured by the Internet Archive on 23 August 2004 depicts a rough schematic showing a semi-conductor substrate with an insulator topped by a gate electrode. An insulating layer rests on the electrode. Above, a source shows electron flow to a drain, producing a voltage differential in an active organic film, responding to an atmospheric irritant. A voltage meter indicates electrical response, passed to an electronic device. The graphic is captioned, 'Transduction of the chemical response to an amplified electrical signal via transistor action.' This project will integrate different scientific and engineering efforts, 'reducing to practice,' as needed for patent or technology transfer. This simplification shows how the electronic device becomes a 'black box,' ready for translation.

The same project on 14 January 2005 [C-2] shows a more sophisticated graphic. The diagram upper right is labeled 'chemosensitive phototransistor' and shows a simpler electrical sensor graphic, with boxes labeled 'indicator,' 'transport,' 'oxide,' and 'gate.' A green wavy arrow points at the 'indicator,' to indicate an environmental substance being detected. From 'transport,' a red arrow shows sensing flow to 'indicator.' On the left side, four bluish patches labeled 'selectivity and sensitivity' indicate chemical materials reacting to specific chemical combinations. The graphic shows two green chemical molecular structure symbols across two boxes, and two red molecular structure symbols vertically stacked by the rows. Interpreted with the phototransistor diagram, patches use the same color for two of four chemical combinations for the environment and in the chemosensitive phototransistor, indicating no reactive response. Two other patches are different colors of blue, indicating specific chemical responses.

This second chart shows progress in producing nanomaterials for sensing specific materials. Accomplishments describe advances in developing and synthesizing new polymers, detecting nitric oxide with a fluorescent material, and creating the novel photodetector to use color change to signal a response to sensor users. Interdisciplinary chemistry and electrical engineering created a sensing system to react with future chemical variations.

## **The Way Ahead**

The methods and data described in this chapter provide the foundation for quantitative and qualitative analyses of research actor-network enrollment and translation activities in the founding era of the ISN, from 2002 to 2007. In four case studies in the

following chapters, I use Internet Archive-captured versions of ISN research project descriptions as foundational primary sources, and augment the information with related publicly available information including reports, news articles, and presentations. Chapter 3 focuses on the ISN's founding as an institution and how participants were enrolled into research networks. Chapter 4 analyzes the 6.1 basic research networks, to understand how those networks function and persist. Chapter 5 explores 6.2 applied research as the venue where users and non-users interact – both in applications of nanotechnology to cancer research, and in inclusion in the research community creating those scientific applications. Chapter 6 highlights 6.3 prototypes and networks which emerge from the ISN, both the ad hoc rapid response network focused on soldier helmet-mounted brain sensors which catalyzed brain research, and the broader networks bringing in undergraduates and West Point cadets to the ISN Soldier Design Competition. These networks expanded by enrollment, creating an institutional generating capacity, and translated capabilities to enable 'action at a distance.' The student teams demonstrated new modes of bi-directional enrollment, teaching their professors how to transition technologies operationally, while their professors taught them nanoscience and bioengineering. Chapter 7 explores conclusions and future areas of research. My goal through this effort is to explore the historical example of an emerging research institute focused on emerging technologies in a new century, looking at groups affiliated with different phases of research, and use quantitative and qualitative analytics to identify patterns of how teams created networks and actions which facilitated technology transitions. I contributed new understanding to STS, highlighting how teams operationalized the translation of nanotechnologies and created bi-directional enrollment.

## Chapter 3.

### 6.0: Founding the Institute: Emerging Technologies, Emerging Institute

#### Overview

After the Cold War ended, United States federal research managers redirected S&T from a defense focus, to seek broader benefits to meet increasing global competition, including investing in nanotechnology. At the start of the twenty-first century, the Army Research Office sponsored a competition to establish an Institute for Soldier Nanotechnologies. Besting fifty competitor university-industry teams, MIT won the contract. The ISN institution opened in 2002 under its first 5-year contract valued at \$50 million in basic research funding plus co-investment by MIT and industry partners. In May 2003, a ribbon-cutting ceremony opened the ISN 2-floor specialty lab facilities for use by more than 150 researchers.

The founding of this federally-funded interdisciplinary nanotechnology research institute provides a useful case study of an emerging institution focused on emerging technologies. Following the example of Actor-Network theorist Bruno Latour in historical analyses of Louis Pasteur's anthrax research, I 'follow the actors' across the events, products, and partnerships that connect them in this historical case study. The institution contract required outreach to enable interested viewers, including citizen-scientists, to learn about the progress of researchers and partners in creating new knowledge and transitioning nanotechnologies to usable forms. Given the ephemeral information about early start-up institutions, I used public information available in 2019 that was provided to educate citizens, partner institutions, fellow researchers, technology transition partners,

and research sponsors. Using STS qualitative methodologies to analyze the case studies along with quantitative technology portfolio analysis of the public presentations and reports by participants, I explore these overarching research questions:

- How were researchers, partner institutions, and research projects enrolled in this institution?
- How did competition and collaboration shape the institution's efforts?
- How did controversy, from external and internal sources, shape and constrain the institution?

The United States invested significantly, and this case study shows how one historical research institution enrolled its participants and emerged from competition, collaboration, controversy, and policy impacts. The investment created an institution of people, partners, and projects with new capacity to produce knowledge and technologies designed to improve human protection.

## **Part I: Founding the ISN**

### **Context of Army Concerns**

After the success of Defense-funded research generated the Internet and miniaturized computing from the space program, the Army sought a new 21<sup>st</sup> century innovation stream to follow these examples which transformed American technology, economy, and society. However, both streams of innovation were nearing maturity and needed to be supplemented with a new path for innovations. Global competition threatened United States dominance in S&T and manufacturing products which had created jobs nation-wide. Federal research since the end of World War II was seen as a

vehicle to increase national security, growth of skilled workers, and job creation.<sup>72</sup> Another driver for Army innovation sponsorship was the challenge of crossing the so-called ‘valley of death’ separating knowledge discovery from usable products and capabilities. In the eyes of sponsors and critics, too many research projects resulted in promising discoveries and early stage technologies that were unable to reach an application for commercial markets. This gap between promising science and impacts in the world amplified concerns that investments in science were not translated to technologies and broader public benefit.

In this context, the Army sought to create a public-private research center focused on nanotechnologies to increase protection for humans, with soldiers as first users. A center could address multiple concerns. The Army applied a new approach, in contrast to the National Science Foundation approach of funding research for 3 to 5 years and accepting knowledge documented in research publications as the primary output. The Army sought tangible results. The knowledge-focused approach had produced nanoscience for decades, but few nanotechnologies had emerged. The Army included competition and venture funding, emulating private industry venture capital for Internet start-ups. To accelerate Defense science and engineering, the Army pursued a collaborative approach, bringing together participants from the Army, industry, and a university in a public-private partnership. By including all three communities in all phases, the Army sought accelerated transitions of research to existing firms and entrepreneurial start-ups. To ensure commitment, all parties invested both funding and people working side-by-side. These co-located partnerships enabled manufacturing practitioners and

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<sup>72</sup> Bush, “Science -- The Endless Frontier: A Report to the President.”

product engineers to shape transitions early, from science to technology, along feasible avenues. Army scientists, engineers, combat veterans, and senior leaders remained involved, increasing research relevance and understanding of soldiers' operational environments. The results were acceptable to the Army research sponsor. The Army repeatedly renewed the ISN in recurring five-year contracts. Founding industry partners continued to fund research and contribute skilled research partners, and more industry partners joined the ISN.

### **Competition for the ISN**

The Army Research Office (ARO) mission is to sponsor extramural research, conducted by universities and businesses outside of the Army S&T research base. Each year, ARO funds more than 1000 extramural primary investigators and students across America. ARO also manages research grants on behalf of the Defense Advanced Research Projects Agency (DARPA). The ARO research sponsorship team began planning for a Soldier Nanotech research center in 1998, and hosted a workshop on nanoscience for the soldier in 2001 that shaped the contract competition.<sup>73</sup>

In 2000, ARO offered a contract for a new nanotechnology-focused University Affiliated Research Center (UARC).<sup>74</sup> Universities view UARCs as attractive research partnerships: strategic investments with long-term, stable federal funding and commitment. Responding to the ARO Request for Proposal announcing the Soldier Nanotech UARC, more than 50 universities teamed with industry partners to compete for

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<sup>73</sup> US Army Research Office, "ARO Workshop on Nanoscience for the Soldier" (February 8, 2001), <http://www.aro.army.mil/soldiernano/>.

<sup>74</sup> US Army Research Office, "ARO Solicitation: Broad Agency Announcement DAAD19-02-R-0001 for Institute for Soldier Nanotechnologies," October 2001, [www.aro.army.mil/soldiernano/finalsolicit.pdf](http://www.aro.army.mil/soldiernano/finalsolicit.pdf).

the contract to establish and operate the ISN. The Army conducted site visits, after the terrorist attacks on 11 September 2001 which gave a new sense of urgency to improving protection for soldiers and emergency first responders.

In March 2002, the Army announced its choice: MIT was selected to operate the ISN. The winning proposal described a collaborative team including faculty and students from many MIT departments, demonstrating multi-disciplinarity. Founding industrial partners included large defense firms Raytheon and DuPont, and medical organizations from Partners Health (the Massachusetts General and Brigham & Women’s Hospitals).

Figure 3. ISN Key Soldier Capabilities and Organization Partners, in “Emerging Technologies from the Army-Funded Institute for Soldier Nanotechnologies,” presented by Army Major Rex Blair, NDIA Pacific Operational Science & Technology Conference, Honolulu, Hawaii, 4 April 2007. (See Fair Use Determination)

The ISN was a significant focused investment in basic research. With co-investment from industry, the ISN consolidated more than \$100 million in investment funding in the first five-year contract. The Army invested \$48 million in basic research funding, to support more than 150 students and research staff. In addition, the Army provided MIT the opportunity to compete for \$20 million in applied research funds, by

partnering with Army S&T organizations. MIT provided \$23 million including a new facility which spanned two floors of advanced laboratory space at Technology Square in Cambridge, Massachusetts. Founding industry partners invested \$15 million and contributed PhD scientists to partner in research. New industry partners provided an additional \$7 million, plus cutting-edge nanotechnology instrumentation.<sup>75</sup>

The ISN mission was to increase human survivability with soldiers as the first customers, then extending capabilities to emergency first responders and the broader community. The first focus areas were protection, performance and enhancement, injury intervention and care. Approaches included creating multifunctional, lightweight nanocomposites; processing and characterizing materials; developing computer models and simulations; and transitioning technologies. Outreach was a core mission, to inform and enroll the MIT community, peer scientific researchers, local communities, defense representatives, and the broader public.

### **From Contest to Controversy**

As part of its competitive bid, ISN founding director Professor Thomas submitted a proposal to ARO that included distinctive cover art. The cover graphic featured a woman wearing a futuristic battlesuit and carrying weapons in an urban landscape. When MIT included this graphic in its ISN proposal publicity, controversy ensued. The graphic was very similar to the Radix comic created by brothers Ray and Ben Lai. As reported in the journal *Science*, on 29 August 2002, the Lai brothers legally notified MIT to cease and desist the use of the image.<sup>76</sup> MIT initially argued 'fair use' for educational purposes.

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<sup>75</sup> Edwin L. Thomas, "MIT Reports to the President 2005–2006: Institute for Soldier Nanotechnologies" (Cambridge, MA, June 30, 2006), <http://web.mit.edu/annualreports/pres06/03.09.pdf>.

<sup>76</sup> Constance Holden, "Comic Infringement," *Science* 297 (2002): 1643.

However, the Lai brothers argued that a \$100 million research center did not equal merely education, but instead represented a major organization with significant resources. The artists argued that a major research enterprise could afford to pay artists and creators fair value for their intellectual property.

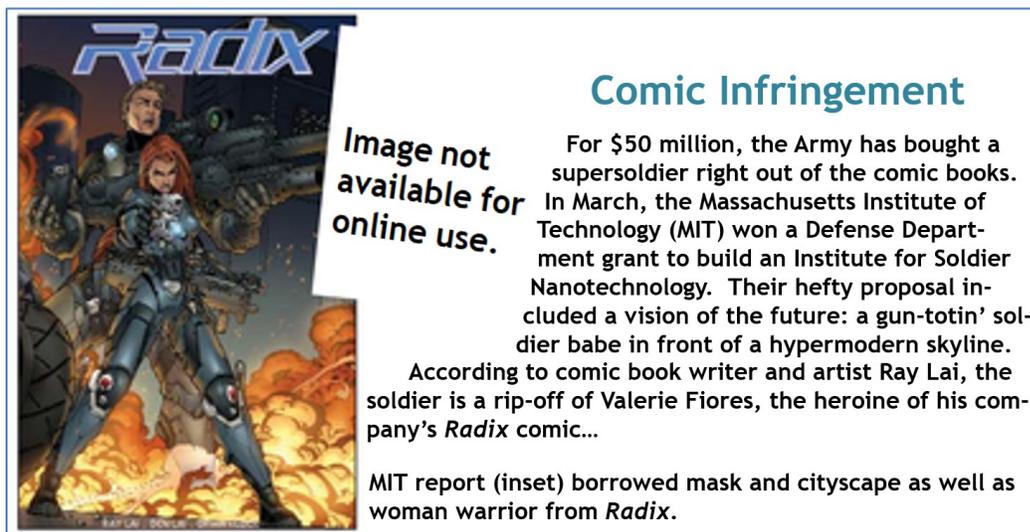


Figure 4. "Comic Infringement," *Science*, Vol. 297, p. 1643, 6 September 2002. (See Fair Use Determination)

With MIT lawyers, ISN founding director Professor Thomas worked a compromise with the Lai brothers. The image was removed from ISN websites and publicity materials. On 30 August 2002, the day after the *Science* journal article, ISN Director Thomas issued an apology. He said, "MIT strongly supports the rights of creators and greatly regrets using the image without permission or credit. I am very sorry that this occurred; it won't happen again."<sup>77</sup> This apology shaped subsequent publications of the ISN, and further complaints were not received. However, the negative publicity also appeared to constrain what publications were released, limiting the publicly accessible archives to help future

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<sup>77</sup> MIT News Office, "Professor Writes Artist to Apologize for Inadvertent Use of Comic Book Image," August 30, 2002, <http://news.mit.edu/2002/thomas>.

researchers understand what happened on a day-to-day basis among researchers at the ISN. Fewer releases of information meant less risk of controversy.

### **Consequences of Controversy**

The controversy raised attention. The *Science* journal article was widely cited and highlighted as negative attention in the media. To be featured in this high-prestige journal is sought by scientists around the world – but not for discrediting actions such as plagiarism or unfounded research results. Individuals or organizations who might have interest in participating in the ISN may well have been rebuffed by the actions themselves, or by the resulting negative publicity. Potential innovators might hold back on disclosing their most creative, forward-leaning thoughts. This type of publicity can create headwinds and barriers to enrollment which must be addressed and overcome for years after such a negative action. The negative impacts cannot be quantified, but clearly shaped the ISN's expressed emphasis on respecting intellectual property rights in their primary research portfolio, as well as the Soldier Design Competition engagements with MIT undergraduate students.

This crisis created an opportunity to shape the ISN's culture in a way that reinforced respect for intellectual property, both for creators and as users. The ISN sharply increased media engagement and outreach. The positive outcome of the controversy was media awareness of the ISN, which led the Internet Archive to capture the research descriptions webpages as part of a lasting digital archive. These artifact captures now provide a key public data resource showing how the ISN changed its presentation to the broader public during its founding era. Other institutions from that early Internet era were not captured, and as a result much ephemeral data is lost to history.

Crisis and controversy early in the life of the ISN created an enduring archive for current day scholars to see the evolution of this emerging institution – rare to see the earliest evolutions of entrepreneurial start-ups and institutions before lock-in.

## **Part II: Leveraging Quantitative Analysis of the ISN Research Portfolio**

People organized into teams with interdisciplinary skills. STS scholar John Law describes this process as 'heterogeneous engineering.' People brought their multidimensional skills to combine with other complementary skills in different people from different departments, and with people at different stages in their careers. All these combinations were designed with a goal of creating nanotechnologies which were ready for technology transition.

### **Technology-focused Research Team Analysis**

Previous STS scholars studied laboratory research teams qualitatively. Bruno Latour and other STS scholars used ethnographic approaches, observing the participants as actors from inside the laboratories studied. This technique can work well, if the STS researcher can gain access to the laboratory as a member of the team or credentialed viewer permitted inside the lab on an ongoing basis. The observer can view how human and non-human actors, processes, and inscriptions produce knowledge which can be translated outside the laboratory. However, outsiders rarely achieve that privileged status of belonging. As a result, later researchers looking back historically must find other mechanisms to analyze S&T focused research.

Latour demonstrated an effective way to 'follow the actors' through time in his historical study of French scientist Louis Pasteur working with partners in laboratory and farmers' fields to study anthrax a century ago. First-person observation is not feasible for

analysts looking back at a historical case study. In my historical study, following these actors required reading their traces in artifacts: studying the literature, reports, and media descriptions published by members of the ISN at the start this century. The core artifacts were the ISN researchers' own descriptions of each research project and the accomplishments published for fellow scientists, potential technology transition partners, interested readers, research sponsors, and the broader public. These project descriptions were updated periodically. During the first contract period from 2002 through 2007, the ISN issued new research project descriptions at least yearly. These project descriptions were captured by the Internet Archive ([archive.org](http://archive.org)), a nonprofit digital library. Those Internet-hosted archives can be viewed freely by anyone who seeks to analyze changes between the versions of digital products that were captured.

By closely analyzing changes between the versions of research descriptions created by the researchers, I identified several patterns of team activity which resulted in observable technology transitions. Quantitative analysis techniques enabled me to identify patterns which advanced technology transition and compare them more broadly to other research projects, across research disciplines. However, this technique is necessarily limited to the evidence available. The authors of the digital artifacts may not be identified, so cannot be interviewed. Co-occurring collaborative or contradicting evidence may not exist, or may not be released to the public. The documents described successes and aspirations, not failures and re-directions. Some re-directions can be inferred from changes in the descriptions, and illustrate how technology-focused research teams follow winding paths. However, even with these constraints, my analysis of transition-focused technology research teams does display patterns of organization which

may be useful for federal technology research sponsors, other university research centers, and individual research teams to understand the many ways technology transitions were accelerated in the first five-year contract era of the ISN.

### Technology-focused Research Team Analysis Framework

This analysis used my research team portfolio analysis framework, using quantitative analysis methodologies described in more detail in Appendix B. I assessed each team using their own project descriptions, rating the start point for each team project within a set of 3x3 quadrants in a Cartesian grid. Ratings placed each team project's orientation from -3 to +3 along two axes: process to product, and science to engineering. Within the quadrants, I analyzed these projects in finer detail, according to the descriptions of activities and accomplishments generated by the research teams themselves, as captured in the ISN project descriptions and reports.

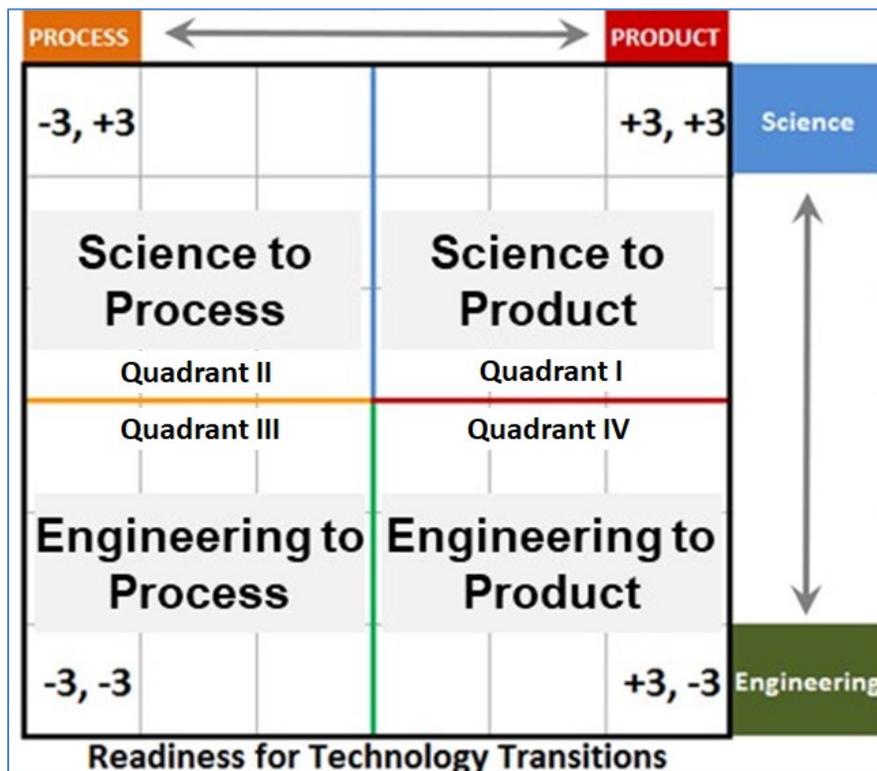


Figure 5. Technology-Focused Research Team Portfolio Analysis (Cartesian Grid).

## **Why Add Quantitative Analysis**

As described in Chapter 2, STS lab studies traditionally focused on qualitative techniques particularly ethnography, to gain understanding of the rich situational details. By adding quantitative analysis, comparisons between unlike research activities can be made, focused on patterns of behavior and underlying dynamics of enrollment. I encoded qualitative data in order to perform quantitative analysis. This quantitative approach enabled me to discern generalizable patterns among techniques teams used while producing a desired output of knowledge plus transitioning technologies. This qualitative approach enables other researchers, observers, or research sponsors to extrapolate these patterns to other technology activities.

## **Team Characteristics**

Teams had to enroll their members and their interested partners, in other teams, industry partners, future student researchers, and Army S&T partners and research sponsors. While performing enrollment activities, team members translate their knowledge to make a difference in terms of technology for soldiers. Some teams may move through the quadrants in sequence, starting with science to understand the fundamental knowledge around a capability, developing the science to create a process, engineering that process to scale up producibility, and engineering a product to transition. Other teams opportunistically found non-sequential pathways to accelerate transitions into technologies. The entrepreneurial processes that these project teams used can inform other transition-focused research teams to find ways in which gain feedback from potential users. The teams describe in this chapter's case studies followed a variety of paths, demonstrating different approaches to accelerate technology transitions. The

traditional linear process does not explicitly provide opportunities for integration of user feedback; each ISN team I describe created opportunities to interact with users and integrated user feedback.

### **Team Patterns of Activity to Achieve Technology Transitions**

In my research team portfolio analysis framework, patterns of activity to transition technologies can be mapped, based on the project plan descriptions. During the ISN's first contract period, some projects leveraged ongoing research. By tailoring the research to focus on soldier needs, the ISN rapidly established a diverse research portfolio. The portfolio encompassed projects from visionary product-focused science, to process-focused producibility processes. Other projects applied engineering to create processed materials into tangible products that can be seen in the world. Transitions could translate the processes of manufacturing to industry or Army S&T members, enabling nanotechnologies to be integrated into other manufacturing processes, or matured into full-scale products before transitioning.

To achieve their goals of transitioning nanotechnologies rapidly, ISN research teams found many ways to accelerate transitions. I argue that the patterns of acceleration by the small teams can be analyzed and compared to other research teams focused on creating technologies to transition, in addition to fundamental knowledge. These ISN outputs included tangible products of materials science, processes to produce and characterize materials, and computational models to simulate these protective capabilities at different size and time scales.

## **Accelerating Technology Transitions**

The ISN emphasis on accelerating technologies to transition led the 55 project teams to employ entrepreneurial approaches to accelerate transitions. The variety of accelerative approaches generated recognizable patterns of team behavior. The teams I studied demonstrated patterns as they accelerated movements from science to engineering for both products and processes. This analytic approach can be repeatable, as other research teams learn how to reach out to industry scientists, Army scientists, and engineers, to accelerate technology transitions. The host agency also created new opportunities to accelerate technology transition, such as providing an on-site technology transfer specialist skilled in integrating emerging technologies into Army systems. The ISN's inclusion of entrepreneurially experienced MIT professors who were experienced in creating market-ready products as the basis of a start-up company. In addition to building on their experiences transitioning technologies to their own start-ups, these professors also created products which could be patented and transitioned through licensing to existing firms. In addition to adding depth to the ISN, these professors had mastered tacit knowledge about transitioning technologies, creating small businesses, and giving their technologies to outsiders to carry forward. The building blocks of putting their technologies into the world shaped how these experienced entrepreneurial scientists partnered, described their research in journal articles, positioned their research teams, and partnered with Army and industry technologists. The ISN founding team, also experienced entrepreneurial scientists, implicitly knew the value of these start-up experiences, and sought to extend this approach to ISN researchers at all levels from faculty to undergraduate.

## ISN Portfolio Analysis of Team Positioning

After I assessed how people organized, using my portfolio analysis, I analyzed team patterns of behavior: how each research team progressed from their initial start point, from science to engineering to either product or process for technology transition. After analyzing each team project's start point, I averaged the overall research teams' positions and mapped the average to my Cartesian grid. Next, I analyzed the progressive movements of the research teams.

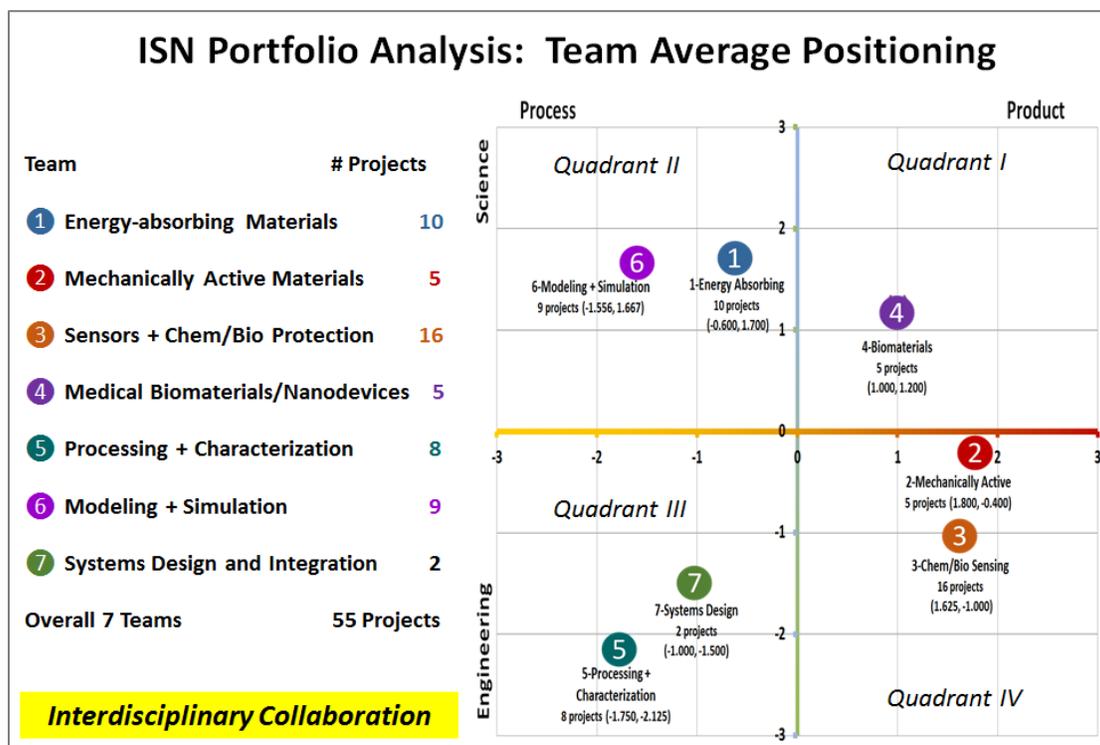


Figure 6. ISN Portfolio Analysis of Team Average Positioning.

### Team 4 Biomedical Materials and Nanodevices

The analysis shows clustering of the different teams in different quadrants, representing their average starting point in the process. Starting from the upper right quadrant, positioned in the most basic product-focused science of quadrant I, Team 4 focused on the science used to make products, in the form of biomedical materials and

nanodevices. Medical devices and biomaterials require additional effort to integrate functional devices into complex human physiologies. To integrate with variable humans, the researchers must solve more problems and understand more complex interactions while creating technologies that can be implemented. During the engineering phase, these biomedical technologies also undergo rigorous testing to comply with federal regulations governing medical devices, demonstrating both safety and efficacy. Partnering with two hospitals who were ISN industry partners, as well as Army medical researchers, proved critical to successful transitions of technologies by these teams, such as needle-less injectors for medical therapeutics.

### ***Team 1 Energy Absorbing Materials***

Team 1, which produces energy absorbing materials, positions its projects primarily within quadrant II, focused on science and early-stage process design activities. However, in order to make processes, material samples must be created, so that the team's positioning is closer to the community of product-focused researchers. Team 1 also performs characterization for their own materials, to qualify and quantify what physical properties are demonstrated. Of necessity, their efforts include creating instruments and developing techniques needed to understand the material characteristics of what materials are being produced. As a result, Team 1 provided support not only internally to characterize their own materials, but also shared the techniques developed with other ISN research teams performing characterization analysis. Their science focused on materials and complementary processes and techniques to understand those materials in comparison to desired attributes. The ISN hired research associates focused on developing new techniques, including how to use nano-instruments such as scanning

electron microscopes, and how to produce and characterize materials using femto-second lasers.

### ***Team 6 Modeling and Simulation***

Team 6 work in computer modeling and simulation also falls into quadrant II. The modeling and simulation efforts introduced computational design spaces and comparatives to real-world materials, which enabled researchers to experiment *in silico* and design materials never observed in nature. Through the design process and molecular-scale modeling, Team 6 supported other ISN teams in creating computational analogs for materials later synthesized in a chemistry lab space, or processed with lasers, or created by other material manufacturing techniques. Team 6 computer simulations would not ordinarily be thought of as technologies which could be transferred, but rather as components of material design and development processes. However, in this first ISN era, Team 6 simulations of impacts of blast and ballistic attacks on brain anatomy created a rich vein of technologies transferred to Defense and veterans-related brain research communities. The increase in Iraq and Afghanistan combat operations produced many soldiers injured by explosives who received traumatic brain injuries. While tranquil times would not create the multitude of traumatic brain injuries observed in combat, the external factors which created those injuries were seen by military leaders as worthy of urgent research to find ways to mitigate the injury impacts. The research studied blast events in detail, both forward in time, seeking to understand future injury remediation, and backward in time, what the military calls 'left of boom' (as early as possible on the timeline before the bomb explodes), to shape protective gear designs, including helmets. Simulations were shared with other researchers to create higher fidelity brain and

skeleton models of human physiology, in order to understand brain injuries and traumas which could harm humans including soldiers.

### ***Team 5 Processing and Characterization***

Team 5 focused on processing and characterization, serving as 'nanofoundries.' This quadrant III team focused on engineering processes which could enable material designs to be scaled up for manufacturability. This team filled a vital role in bridging the divide between an isolated and protected laboratory, and the manufacturers needed to produce materials reliably and at economic scales. These researchers had to understand both the core science and also current manufacturing processes used in American factories. In many instances, these researchers invented new ways of providing nanomaterials as additives or composites with other materials. For example, several projects focused on applying nanomaterials as coatings applied by mist onto other materials. The engineers required understanding the interaction between each layer of the materials and the amount, sequence, and configuration of materials sufficient to be active for each envisioned application. A chemical vapor deposition mist could cover individual fibers of a material with waterproofing substance, but needed to be engineered to provide ways to waterproof the gaps between individual fibers. This requirement balanced waterproofing with fabric breathability, to be comfortable for people who sweat during strenuous activities. The teams developed a wide range of techniques. New material approaches included extruding fibers which integrated electronic components, and spinning mats out of nanomaterials, and chemically depositing electronic components for devices. All these team projects fall within quadrant III.

## ***Team 7 System Integration and System Design***

Also, in quadrant III were overarching Team 7 system integration and system design projects. These projects focused on how to scale up nanodevices created by ISN teams into portions of soldier battle-worn or battle-borne ensembles. Here, the combinations and sequences of materials had to provide beneficial functionality, while not introducing vulnerabilities that do not work in soldiers' operational environments. For example, a material that is waterproof but noisy would not be beneficial to soldiers who need to move quietly during sensitive operations. Similarly, material which is optically invisible to the naked eye but which glows under thermal viewers could be counterproductive to integrate into soldier gear, because these materials could be easily detected in nighttime conditions. However, that same material which might not suit soldiers could benefit first responders such as firefighters, formed into thermally-viewable markers on uniforms that could be seen in obscured smoky conditions. Similarly, this type of thermally-visible materials could be added to floatation devices and marine uniforms, to detect sailors who fall overboard in choppy seas. These examples show how materials which may suit one operational environment may not fit another, and also how materials which are entirely unsuitable for certain attributes in one context can be very useful in another context. As described in STS case studies including the use of the automobile in US society, users and non-users shape social-technological capabilities.<sup>78</sup> Users needed opportunities to inform designers of their operational environments to shape ISN technologies.

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<sup>78</sup> Nelly Oudshoorn and Trevor Pinch, eds., *How Users Matter: The Co-Construction of Users and Technologies*, Inside Technology (Cambridge, Mass: MIT Press, 2003).

### ***Team 2 Mechanically Active Materials***

Finally, in quadrant IV, the Team 2 mechanically active material projects and Team 3 chemical biosensing projects both focused on engineering products that could be integrated into capabilities to increase human protection. The mechanically active materials team included a several projects which could rapidly provide prototype products, such as flexible materials that could be hardened on demand to provide a splint for an injured ankle. The primary characteristic of the mechanically active materials was multifunctionality. The materials needed to be wearable in a common configuration, and then simply and rapidly changed into a different configuration to provide on-demand benefits.

### ***Team 3 Chemical and Biological Sensors***

Team 3 chemical/biological sensors projects tended to be even closer to products than Team 2, by the nature of the targets. The sensors were designed to react to specific environmental materials, in order to detect harmful agents. In order to design a sensor, a specific target threat had to be chosen and characterized. That very specificity meant that the sensor could be demonstrated to work with a chosen surrogate, approved by the sponsoring agency, and tested under more realistic operational environment in a variety of scenarios. To assess value added and constraints of a sensor, researchers had to prototype realistic versions.

### **ISN Project Patterns of Enrollment**

Each of the 55 project teams in the seven overall teams positioned their projects in a manner which illuminates the trade spaces between science and engineering focus, and process and product implementation. All teams demonstrated interdisciplinary

collaboration and more cross-team leveraging of talents and research than an outsider might expect.

## Rapid Technology Transition in FIDO Explosives Detector

The FIDO explosives detector provides an example of both enrollment and of progressing through the quadrants in sequence, rapidly. Professor Timothy Swager led a team that developed a novel material, amplifying fluorescent polymers (AFP), which reacted to specific hazardous substances in vapor. Ordinarily, these polymer materials would emit a visible light when exposed to ultraviolet light. However, when targeted hazardous materials were present, those particles bind with the polymers, blocking light emission. Professor Swager used the metaphor of a strand of holiday lights, which remain dark if a burned-out bulb blocked transmission of the signal.

**Science Making a Difference for Soldiers:  
FIDO Explosives Detector**

**MOLECULAR ENGINEERING:** designed molecules

**OPTICAL ENGINEERING:** integrated Detector/Sampler

**REPACKAGING:** from DARPA Dog Nose concept to real Warfighter Device

**SCIENCE:** Amplifying Fluorescing Polymer (AFP) developed by MIT ISN Prof Swager glows green, but quenches when TNT is present.

**Assessments:** USMC in Iraq (2004), ATEC in Iraq (2005)  
**Procurements:** SOCOM (2005), PMs (2006) for handheld + robot-integrated

**DETECTION OPPORTUNITY:** Hidden explosives give off traces of chemicals, which may be detected.

**Army's Greatest Invention Award 2005**

Rex.Blair@us.army.mil Mar 2007

Figure 7. Science Making a Difference for Soldiers: FIDO Explosives Detector, in “Emerging Technologies from the Army-Funded Institute for Soldier Nanotechnologies,” presented by Army Major Rex Blair, NDIA Pacific Operational Science & Technology Conference, Honolulu, Hawaii, 4 April 2007. (See Fair Use Determination)

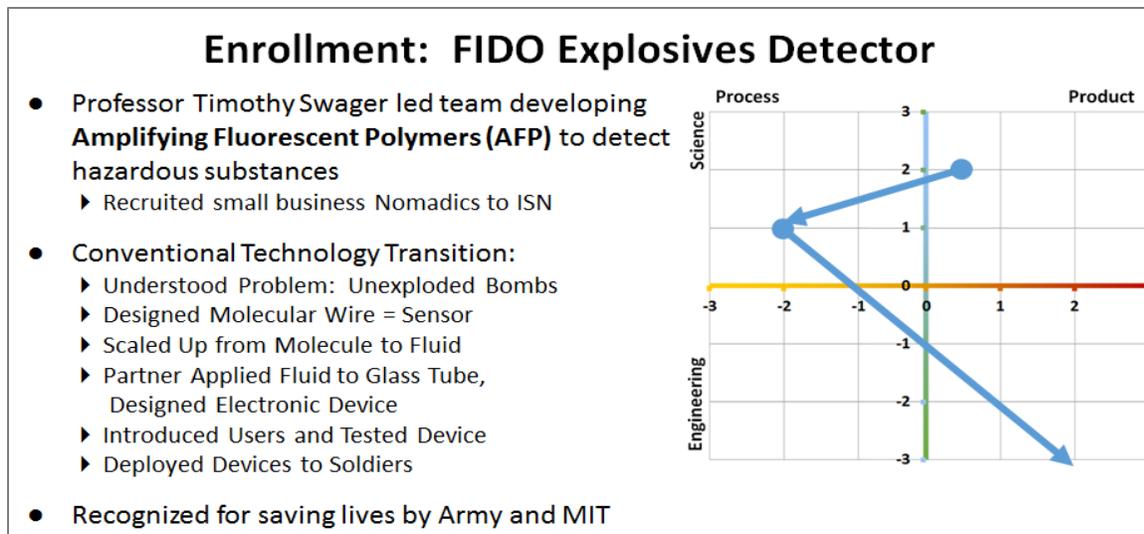


Figure 8. Enrollment: FIDO Explosives Detector.

Once the detection material was created and designed to be sensitive to specific hazards, Professor Swager recruited and enrolled an Oklahoma small business called Nomadics to become an ISN industry partner. Professor Swager’s team, including a graduate student named Aimee Rose, MIT PhD 2003, scaled up the material and transitioned the product to the small business. Dr. Rose also transitioned to the small business as an employee in their new Cambridge, MA office. The small business engineered a prototype system which included glass capillaries coated with AFP polymer, a fan system to pull in vapors suspected to have the target particles, a detector to see if the polymer emitted any light, software to compare prior state with each new observed state, and a computer display to provide feedback to the user – literally, ‘black boxing’ the detection process. Users holding the FIDO explosives detector could know if there was a change in the ambient environment indicating the presence of the hazardous material for which the system was tuned. Users could react to the computer display, or to a Geiger-counter-like audio signal, to search their environment for vapors triggering the response, and take prudent operational response to explosives before the explosion – ‘left of boom.’

The sensitivity of the response to particular materials was sufficient that FIDO users could use the device to sniff the hands or clothing of people suspected of handling particular types of explosives in the near past, and respond to the device signal.

This capability demonstrates a conventional technology transition. The research team understood the problem: detecting unexploded bombs. First the team decomposed the problem into its component parts, and identified the most frequently occurring types of explosives in the combat zones where soldiers currently operated. Next the team collaborated across academic disciplines of chemistry and electrical engineering to design a polymer to serve as a molecular wire, a sensor, exquisitely tuned to detect particles of that most frequently occurring explosive. The chemists scaled up the design from a single designed molecule, simulated in the computer, to a polymer fluid. Chemical engineers partnered with the small business to apply the fluid to capillary glass tubes. The partner company designed a simple handheld device that was robust, continuing to work after being dropped or driven over by a vehicle, and easily understood by distracted users in tense conditions. The device provided both visual and auditory feedback to a soldier or an allied partner who was holding it. The device design did not require fluency in English, or even literacy, crucial for interoperability with partner soldiers and non-soldiers from different countries. The devices were tested at ranges and in user tests. At special ranges, government test personnel assessed functional responses to various types of explosives, at different concentration levels, testing for results that were false positive (indicated explosives when none present) and false negative (indicated no presence when explosive existed). Users tested operations, maintenance, and suitability in the operational environment. Once the tests successfully demonstrated sufficient

capability and sensitivity for the agency sponsor to find merit, the Army procured a large quantity of FIDO explosives detectors and deployed them to support operations in both Iraq and Afghanistan. The devices were shared with partner organizations, including host nation police who were providing defense against explosives.

In another use of competitions, the FIDO device was recognized by the Army as one of the 'Army's Greatest Inventions' in 2005.<sup>79</sup> The Army lauded this simple handheld system for saving soldiers' lives and reducing the impact of explosives on local civilian populations which the soldiers were protecting. In 2006, the FIDO device received another recognition as one of the Army's greatest inventions of the year, when FIDO placed on a small robotic system enabled the operators to remain a farther distance away from potential explosives. Instead of putting soldiers or partners into harm's way, the robot enabled the device to be able to explore objects at a greater stand-off distance, increasing user safety. The MIT community similarly recognized Professor Swager with the 2007 Lemelson-MIT Prize for innovation. The Lemelson award recognized the ingenuity of this new class of polymers and the efforts of the creator to get his creation into devices that made a difference by saving lives.

### **ISN Project Patterns of Enrollment: Medical Enrollment**

A second pattern of enrollment, partnering on medical projects, was demonstrated by MIT Institute Professor Robert Langer, who led two biomedical projects on team 4. One project focused on switchable surfaces. This project was a quadrant I novel scientific discovery project that he proposed. His concept was to design a molecular structure that

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<sup>79</sup>Lemelson-MIT Program, "Timothy Swager, 2007 Lemelson-MIT Prize Winner," April 2007, <https://lemelson.mit.edu/resources/timothy-swager>.

was hydrophilic, meaning that it allowed water to pass through the pores of the polymer substrate. When activated by an electrical or chemical charge, the material changed to be hydrophobic, blocking liquid transfer. The novel approach used a secondary property of increasing density of conformation of the molecular strands when changed from hydrophilic to hydrophobic. Essentially Professor Langer proposed to create widely dispersed molecules which stood perpendicular to a surface, then bent over to touch their tops to the surface when electric charge had changed. As the material became hydrophobic and blocked liquids, this activated state would be more rigid than the inactivated state, thus forming a barrier. The protective barrier could be a splint on demand, or integrated into a uniform could serve as a built-in tourniquet. This approach was novel, both in concept and in execution. Professor Langer leveraged his prestige and renown as an institute professor to gain partner buy-in. He had demonstrated success scientifically with many publications and patents, and as an entrepreneur had started companies, and other companies licensed his inventions.

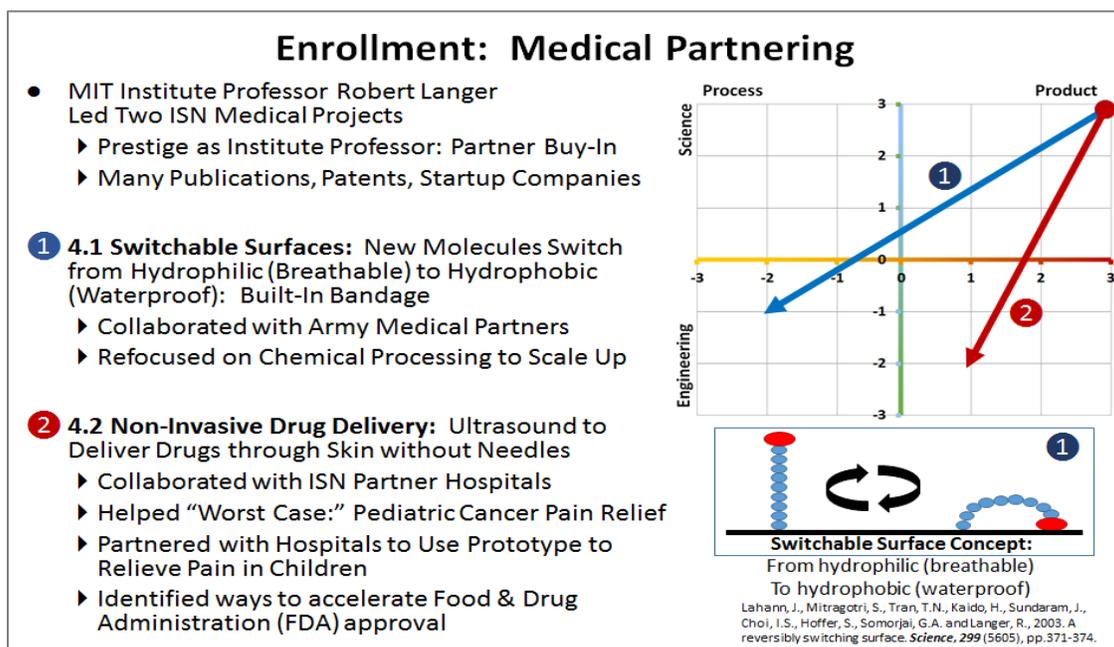


Figure 9. Enrollment: Medical Partnering with Projects led by MIT Professor Langer.

Project 4.1 focused on creating switchable surfaces, a new design of molecules that changed from hydrophilic to hydrophobic: candidates for bandages built into soldier suits. [The 2004 ISN marketing video featured this concept.] To translate vision to reality, Professor Langer collaborated with Army medical partners. Based on feedback from Army researchers, Langer understood the challenge was solving issues with chemical processing to scale up production.

Project 4.2 on noninvasive drug delivery brought Professor Langer to collaborate with Massachusetts hospitals who were ISN industry partners. His concept used ultrasound to deliver drugs through layers of the skin without requiring needles. [This concept was also featured in the ISN vision video.] He collaborated with ISN partner hospitals to prototype this capability, identifying a target population which needed this solution to solve a difficult problem: pediatric cancer patients. These children needed pain medications and therapeutics which were delivered intravenously. However, over time, their veins could no longer handle additional amounts of fluid pushed through them. Doctors, patients, and families faced difficult choices about therapeutic priorities. The problem could be mitigated if alternative delivery mechanisms could provide therapeutics through different channels. Needle-less ultrasound transport reduced the volume of holes in the skin surface needed to transport pain-relieving agents, so that smaller skin holes could be used to deliver therapeutic agents. This approach increased the available skin pathways for each patient to receive therapeutics and pain treatments.

Another enrollment activity occurred with federal regulators. Because this population lacked solutions to a difficult problem, regulators were amenable to limited

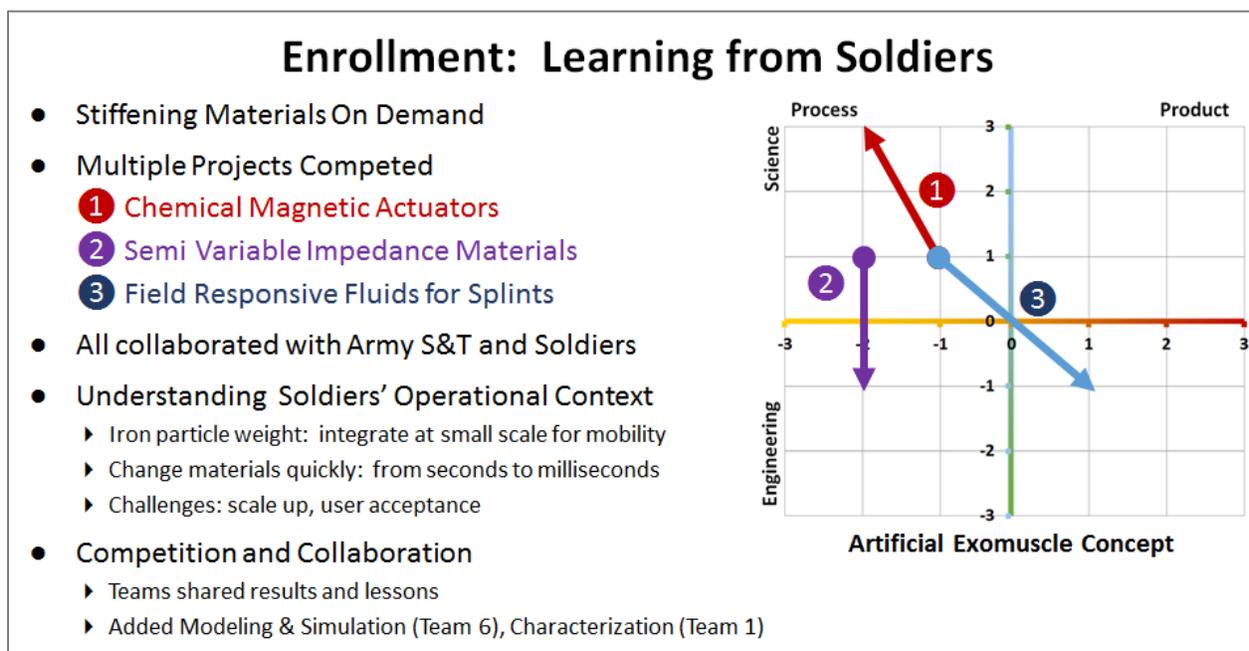
tests, streamlining traditional animal testing before human testing in order to accelerate these devices for a needy population. Professor Langer had credibility and a record of success in the delivering medical therapeutics and devices, which provided the basis for trust and enrollment for regulators, hospitals, doctors, patients, and patients' families. His successful track record as an entrepreneur enabled a start-up business to be built around this medical device, marketed under the name SonoPrep. In this example of technology transfer, commercial use preceded military use.

This project demonstrated enrollment of the medical partners, but also demonstrated the difficulty for outsiders to distinguish the sources of funding for projects. Professor Langer was not unique in receiving funding from multiple research sponsors. Only an insider with deep understanding of the ways in which research was segmented and interrelated could discern which funded efforts built on other funded efforts. Research publications do provide acknowledgements of the funding source for the published research. However, in practice, multiple publications on different, complementary aspects could describe a given technology being transitioned. The application of a novel approach or capability to a new domain, such as biomedical devices integrated into a specific concept of soldier battlesuit, could require specific scientific and engineering approaches to apply a specific capability.

### **Bi-Directional Enrollment and Learning from Soldiers**

A third pattern of enrollment demonstrated by teams at the ISN, and one explicitly sought by Army research sponsors, was learning from soldiers. One example was teams working on the category of materials which stiffen on-demand, to make splints or other protective materials. The novelty of having variable resistance material could change

operations for soldiers, who then wore heavy, hot, and hard-to-move ceramic armor plates in body armor to protect them against ballistic injuries. Three different categories of project both competed and cooperated in this category of challenge. The chemical magnetic actuators project sought to respond dynamically to a rapid penetrating attack by a bullet or knife. The semi-variable impedance materials project sought to transform flexible garments into stiff protective armor on demand. The field responsive fluids project sought flexible sides in soldier boots and kneepads which soldiers could transform into a splint on demand without needing to carry extra materials.



*Figure 10. Enrollment: Projects Learning from Soldiers.*

All three projects started in quadrant II, focusing their science on processes. The scientists sought to solve the material problem, but many found themselves without a clear understanding of the holistic environment in which soldiers operate. For example, using large amounts of iron particles for material to change impedance could increase armor protection, but would be heavy when used in enough quantities to protect. In order

to understand the military operational environments, all three research teams collaborated with soldiers in Army researchers. The ISN leaders organized visits for primary investigators to observe soldiers training in person, at Army bases in Louisiana, Georgia, Missouri, and the California desert.

The collaboration worked both ways. The ISN researchers learned about the constraints of operating in soldier environments, and the tradeoffs between reducing the weight soldiers carried while increasing protection. Army researchers learned about emerging materials and shaped requirements for future projects to take advantage of new capabilities enabled by the materials. In this way, the researchers who worked on basic research could tune their approaches early in the design phase. Army researchers could accelerate applications by figuring out which problems to solve first to use these nanotechnologies operationally. Army researchers brought relevance on how to use the novel protective materials while minimizing negative aspects.

This bi-directional enrollment refocused research projects to increase relevance to soldier needs. Iron particles can protect, but are heavy; new mechanisms of integration were needed to gain benefit from iron ferrite nanoparticles. Rather than using iron as a bulk material, narrow tubes filled with iron particles could be threaded through specific parts of soldier uniforms, and activated magnetically. These novel applications could be flexible, and provide on-demand improved protection at an acceptable weight and speed. Understanding the speed of ballistic threats in combat required researchers to learn that the change from flexible to rigid had to occur within milliseconds; seconds were too slow to be relevant for protection. The concept of scale-up was particularly challenging, given these operational constraints of actual use by soldiers. User acceptance was critical

to make adoption of technologies work in the real world. Early enrollment and continuous engagement with soldier-customers overcame many challenges and led to acceptable and useful nanomaterial solutions.

In addition to the internal-external collaboration with soldiers as representative users and Army scientists as practitioners who understood how to scale up research to meet soldier operational needs, research teams both cooperated and competed to provide solutions for soldiers. Teams shared their results and lessons learned. Each team integrated with a modeling and simulation project, from Team 6, as well as materials characterization projects, from Team 1, to understand and describe the functional characteristics in their different states. As a result, the projects advanced not only splint-on-demand projects, but also novel approaches to artificial exomuscle made with nanoparticles. The Army knew how to ask for splint-on-demand materials, but advancements in possibility created by these research teams opened new avenues for artificial muscles. Only by moving through these introductory projects could more advanced materials science and engineering efforts be envisioned and take place.

### **Using Enrollment to Accelerate Science to Technology**

A fourth approach to enrollment was demonstrated by small teams focused on accelerating science to technology. These teams operated independently, and demonstrated less collaboration with other ISN teams; integration was limited. However, the principles that their projects demonstrated opened new avenues of exploration in nanotechnologies.

One of these projects was led by Professor Linda Griffith, who created a microfluidic device to replicate organs for medical testing, called 'liver on a chip.' This

project initiated in quadrant I and rapidly moved to quadrant IV, with the goal of being used by hospitals and medical researchers to test toxins in a functional replica of a human organ. This would enable earlier human testing of biopharmaceutical materials, far sooner than traditional testing. Since this device was a biomedical device which would become part of the biomedical testing pipeline, regulatory approval by the FDA would be required. Having partnerships and collaborative networks with the hospitals allowed researchers on this project to accelerate their transition from science to technology.

A similar effort was a different type of microfluidic device by a different ISN research team focused on testing the flow of fluids with potential toxins past sensors at the microscale. These devices offered the potential for hazard sensors to be built into soldiers' uniforms or carried by soldiers. This project team moved rapidly from quadrant II to quadrant IV, accelerating the transition from a process to a sensor that could be integrated in a variety of ways.

A third project, led by Professor Vladimir Bulović, sought to leverage new techniques of vapor mist deposition of materials needed for electronics to create conformal electronic devices. The ability to have flexible and resilient electronics has long been sought for Army, astronaut, and first responder uniforms. Commercial uses would include lead users in the outdoor recreation community, including hikers, mountain climbers and other outdoor enthusiasts. The ISN accelerated the possibilities of these new types and form factors of devices to meet a variety of new needs. Initial prototypes could be presented to and discussed with potential users, to shape future applications of the core technology – particularly crucial as the smart phone emerged as a ubiquitous technology platform and enabler.

Finally, Professor Barbastathis explored new ways to create three-dimensional objects from two dimensional substrates with techniques he compared to origami. His nanoscale-origami projects sought to increase producibility, demonstrating acceleration from quadrant II to quadrant IV, in order to create devices which exploited properties which change at the nanoscale.

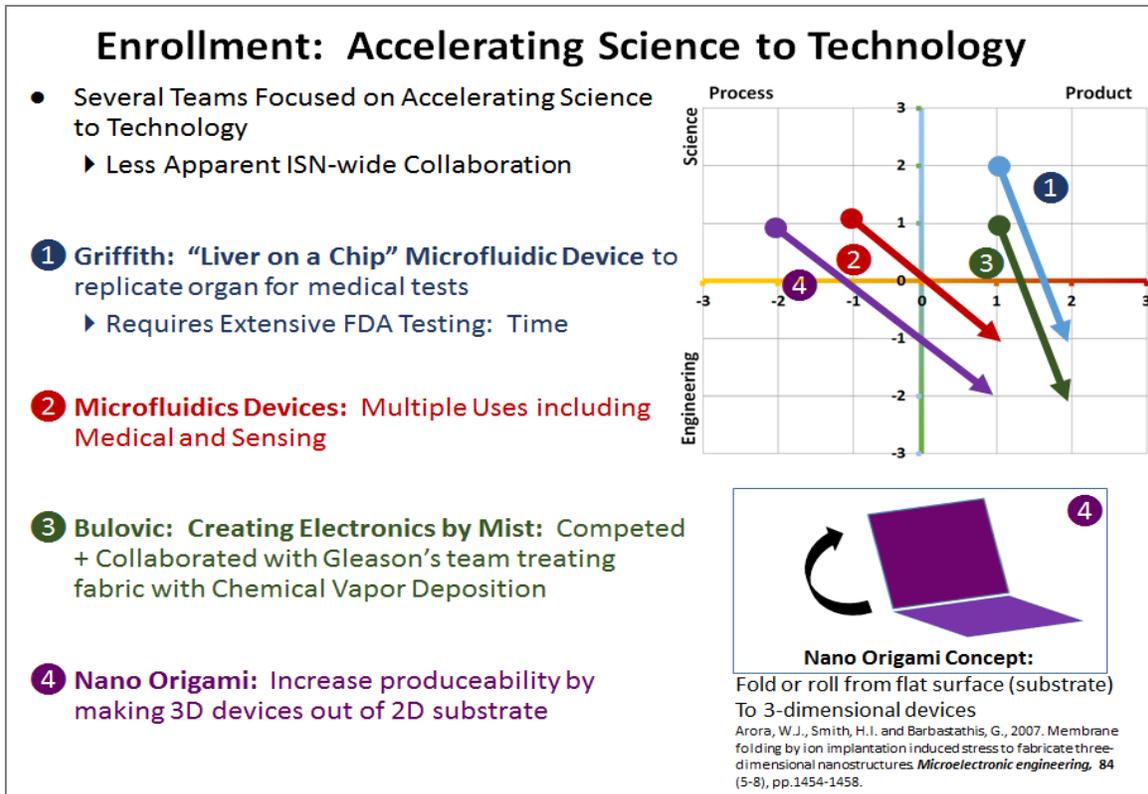


Figure 11. Enrollment: Teams Accelerating Science to Technology.

All four of these projects benefited from participation in the ISN, and close collaboration with Army research sponsors, visiting soldiers, industry, and partners in Army S&T teams. The feedback gained helped shape and accelerate transitions to technologies, which created both benefits and challenges. The industry and media awareness of these potential projects created competition for the teams which may not have existed without the media awareness. For challenges previously seen as

unachievable, the existence of these prototypes demonstrated potential approaches, and the media attention demonstrated potential markets: competitors emerged to address the same challenges. In this way, participation in the ISN could prove to be a double-edged sword.

### **Using the ISN Soldier Design Competition to Enroll Undergraduates**

A final pattern of enrollment to expand the intellectual community of researchers engaged around the ISN involved adding undergraduates. In a clear example of the heterogeneous engineering described by STS scholar John Law, ISN Director Thomas described in his report to the MIT President the process he used to add additional researchers to round out the ISN research portfolio.<sup>80</sup>

In a speech to the MIT community, Professor Thomas also described the goal of expanding the ISN community to include undergraduates. To enroll undergraduates and create deeper relationships with Army participants in the training community, beyond the scientist-to-scientist relationship with Army S&T, the ISN established a new competition called the ISN Soldier Design Competition (SDC). MIT was known for entrepreneurship competitions, which in this timeframe expanded in focus from commercial success to enhancing global social good. Even though students would be volunteers and would receive no academic credit, ISN leaders believed that the competition would enroll students, prize sponsors from industry partners, challenge sponsors from the broader Army community, and mentors from Army graduate students on campus and Army researchers at nearby Natick Soldier Center. The competition did prove very successful

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<sup>80</sup> Edwin L. Thomas, "MIT Reports to the President 2003–2004: Institute for Soldier Nanotechnologies" (Cambridge, MA, June 30, 2004), <http://web.mit.edu/annualreports/pres04/03.16.pdf>.

as a mechanism to increase undergraduate enrollment, and had side benefits of giving the ISN positive media coverage throughout the academic year.

The competition was structured with six defined challenges, each with an Army mentor who would provide information and advice about practical soldier requirements. The competition also included an open undefined challenge, empowering undergraduate teams to propose a problem to solve for soldiers and first responders. Student teams could propose a problem, but could not include weapons or classified materials. One MIT faculty researcher wrote to the campus newspaper, urging the broader focus on non-military humanitarian applications to improve the lot of human beings everywhere.<sup>81</sup>

Although nanotechnology was not required, novel working prototypes were mandatory. Novelty was defined as patentable, which reinforced the concept of respecting other people's intellectual property rights. Novel, working prototypes also enabled viable pathways to commercialization if teams pursued those opportunities. The SDC started with giving undergraduates reason to build teams together. Each team needed to define their problem, and seek guidance from Army mentors. Next, each team proposed a solution and presented their concepts to judges at the competition semi-finals. Selected finalist teams created working prototypes, and demonstrated prototypes with their 'elevator pitch' to a panel of distinguished guests at the SDC finals in front of a live MIT audience. Judges included senior leaders from the Army, academia, and industry. Each panelist voted a score for each prototype to identify winners of the various prizes, which were provided by industry partners of the ISN. Prizes had no limitations on use, and imposed no equity-diluting concerns about student team intellectual property rights.

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<sup>81</sup> Martin Hunter, "The Soldier of the Future," *The Tech*, September 20, 2005.

Over dinner, judges received presentations about ISN nanotechnology research and mingled with ISN researchers. Faculty members observed the positive engagement with Army sponsors and major entrepreneurs, and learned benefits of creating technologies for transition: fame, accolades, monetary rewards, and opportunity to create viable start-up businesses. These positive forces reinforced the ISN's focus on creating and accelerating technology transitions.

Student teams benefitted from *pro bono* advice and resource identification, including *pro bono* MIT Venture Mentoring Services. The MIT Technology Transfer Office assisted researchers for projects with intellectual property encumbered by MIT research funding. Student teams could use common MIT resources such as the Machine Lab and computing infrastructure without impinging on their intellectual property rights. This awareness of intellectual property rights encouraged entrepreneurship, enabling teams to create a start-up company, and reinforced hard lessons learned from the Radix controversy.

### **Translating Knowledge from Students to Faculty**

Knowledge about the ISN and the research was increased by publicity around the student competition. After the initial year, publicity around the SDC increased the desired positive media attention. The ISN hired an SDC coordinator who was also a research associate. The candidate chosen happened to be an Army veteran who graduated from the United States Military Academy at West Point. Based on his network, he reached out to West Point faculty to extend the opportunity to participate. The West Point cadets used the SDC to showcase their engineering capstone projects. This enrolled them as students, as well as the faculty who returned to the active Army after teaching at West

Point, aware of new S&T capabilities and networked with the inventive researchers at the ISN. Awareness increased demand for these protection capabilities.

Across MIT, the SDC increased faculty awareness of the ISN and the opportunity to create technologies to benefit Army users and first responders. Student awareness of 'how to' transition projects created patterns, and the number of start-up businesses was increased among both faculty and students. Industry increased their engagement with members of the ISN community in informal, short-term, low-risk projects. The social enrollments generated new networks.

**ISN Soldier Design Competition: Dealing with Success....**

**Army & Marine Challenges Ensure relevance**

**Directional Gesture Communication System**  
 SDC-1: Digitized Hand-Arm Signals with Personal Direction Reference: Incorporated as RallyPoint, Inc., won 2 Army SBIRs (\$750K) for Future Force Warrior (FFW) Handwear Computer Input Device

**ATLAS Powered Rope Ascender**

**USMA Team Supercharged**

**SDC2: Battery Power Scavengers:**  
 PEO Soldier – 2 designs (MIT + USMA) for Soldier field testing by Fall 2005 (\$250K); FY07 contract for Iraq

**MIT Team Xitome: Kailas Narendran, CEO**

1) \*Rocket launches to 100 meters  
 \*Transmits video data down to ground robot  
 \*Flight time: 10 sec.

2) Ground vehicle relays data to control station

3) \*Control station processes imagery  
 \*Displays mosaic of 1 km area around ground vehicle  
 \*Allows operator to zoom in on objects of interest

**TacShot**

**Goal: Involve undergrads in ISN**  
 → Solve real problems, to help Warfighters  
 → Involve military: USMA, mentors, judges  
 → *Innovate to make a difference sooner!*  
**technology for Warfighters**

Rex.Blair@us.army.mil

Mar 2007

Figure 12. Undergraduate Volunteer Teams in ISN Soldier Design Competition, in "Emerging Technologies from the Army-Funded Institute for Soldier Nanotechnologies," presented by Army Major Rex Blair, NDIA Pacific Operational Science & Technology Conference, Honolulu, Hawaii, 4 April 2007. (See Fair Use Determination)

### The Device



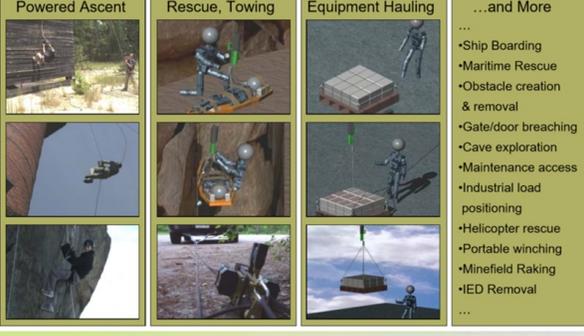
**Original Challenge:** 50 ft in 5 seconds with 250 lbs  
 -Device Weight: <25 lbs!  
 -5 kW Mechanical Output in 25 lb package

**Team ATLAS Original Design:**  
 -Similar to Cordless Power Tool  
 -High Output DC Powertrain  
 -Innovative Capstan Mechanism  
 -Achieved 50 ft in 7 seconds with 250 lbs

**Current Model: SRA03-1**  
 -17 lbs total weight  
 -350 lbs at 5 ft/sec  
 -600 ft vertical per charge

$$T_1 = T_2 e^{(\mu\theta)}$$

### Multiple Iterations, Multiple Uses



**Powered Ascent**

**Rescue, Towing**

**Equipment Hauling**

**...and More**

- Ship Boarding
- Maritime Rescue
- Obstacle creation & removal
- Gate/door breaching
- Cave exploration
- Maintenance access
- Industrial load positioning
- Helicopter rescue
- Portable winching
- Minefield Raking
- IED Removal
- ...

Figure 13. ATLAS Powered Rope Ascender, in “Emerging Technologies from the Army-Funded Institute for Soldier Nanotechnologies,” presented by Army Major Rex Blair, NDIA Pacific Operational Science & Technology Conference, Honolulu, Hawaii, 4 April 2007. (See Fair Use Determination)

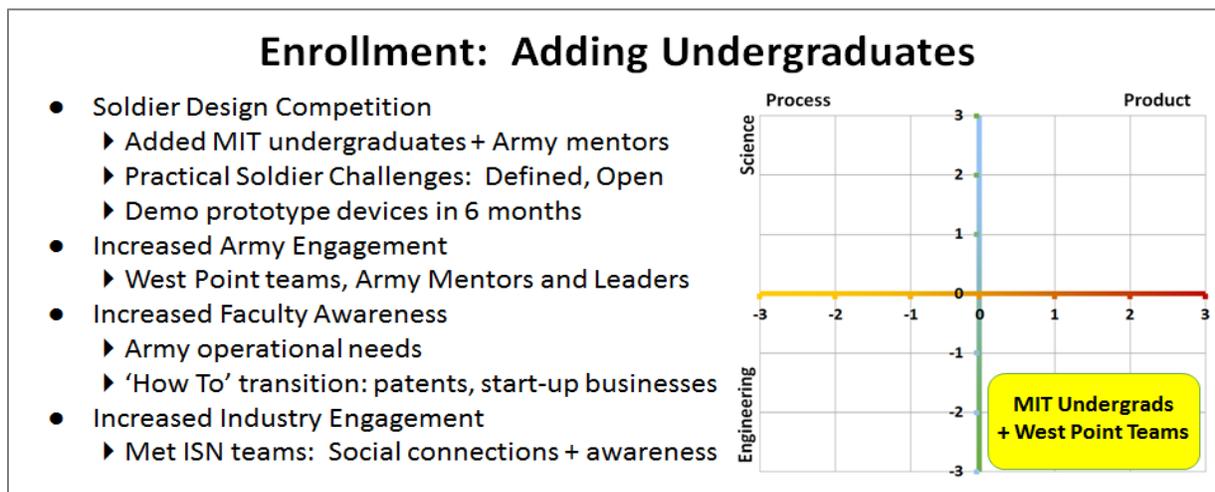


Figure 14 Enrollment: Adding Undergraduates via the Soldier Design Competition.

Several student teams created their own start-up businesses. The ISN leaders featured these small business entrepreneurs in other SDC events. One team, RallyPoint, created a glove platform for a gesture-based computer input device. (These student prototype case studies will be discussed in greater detail in Chapter 6.) While continuing their education, these students created a small business, formed around the patent for their device, and successfully competed for and won an Army Small Business Innovation Research (SBIR) grant worth \$750,000. Their device was integrated into the Natick

Soldier Center Future Warrior S&T project, marking the transition from a student project to a major Army innovation program. A similar success was seen by a team called ATLAS Devices, which created a portable lift device comparable to a hand-carried elevator. Like RallyPoint, ATLAS created a business around their patent and received contracts from the Army and Marine Corps to purchase multiples of their portable lift device. In addition to military applications, local police and fire departments also purchased ATLAS devices for emergency rescue operations. Other student team prototype projects included a portable water purifier and several designs of battery power scavengers.

One of the most ambitious SDC projects was a helmet mounted blast dosimeter. This project accelerated a major Army effort to procure, test, and deploy 10,000 soldier helmet sensors to detect traumatic brain injury for soldiers deployed in combat in Iraq and Afghanistan. The Army officer who was the MIT graduate student affiliated with the blast detector team, Major Luis Alvarez, was cited as an inspiration in the MIT webpages about the SDC. He later transferred to the Natick Soldier Center to increase the networks and collaboration opportunities between Natick and the ISN, transferring technology in his person.

All these student projects created engaged teams who brought together undergraduates in the MIT community across many departments to bring fresh perspectives and entrepreneurial energy to the ISN community. Undergraduates who became aware of the ISN through the SDC later applied to be graduate students at MIT working in the ISN on graduate funded research. Members of the Army who were completing graduate degrees at MIT and Harvard became more closely aware of the advanced research being done in academia on behalf of their agency. Faculty members

became aware of the opportunities and the expectation of successful creation of devices which could be patented and transitions either through small businesses or through industry partners to meet ISN goals. Overall, the SDC strongly reinforced the ISN's entrepreneurial ecosystem.

### **ISN Outcomes: Capacity Building to Create New Institutions from the Institute**

In addition to the individual technologies that were successful, an important measure for the performance of the ISN was the capacity to create institutions which in turn created capacity to expand. This generative function can be observed at multiple levels. At the individual level, post-doctoral associates and dozens of graduate students performed and published research and dissertations. These people emerged from their ISN experience equipped to practice nanotechnology in a variety of roles in academia, industry, and government research and policy making. Human capital was enriched.

The same capacity building occurs at the level of faculty primary investigators, leaders of research teams. Faculty members such as Professor Raúl Radovitzky participated in and expanded the broader Defense brain science community. He contributed by creating computational models to simulate types of events suspected of contributing to traumatic brain injuries soldiers received in combat. In other institutional capacity building, Professors Paula Hammond and Angela Belcher extended their collaboration to focus on cancer particle development under a new MIT cancer research institute with financing provided in part by the Koch Corporation. Professor Vladimir Bulović built on the nanotechnology concepts in leading a new nano institute at MIT.

Professor Yoel Fink built on the ISN institution and technology transitions to create a new type of partnership in the MIT-founded Advanced Functional Fabrics of America (AFFOA) Institute. Secretary of Defense Ashton Carter announced the center and described the \$317 million public-private Manufacturing Innovation Institute: “The partnership includes 32 universities, 16 industry members, 72 manufacturing entities, and 26 start-up incubators, spread across 27 states and Puerto Rico.”<sup>82</sup> The desired output is integrated fabrics and ‘wearable devices’ based on functional fiber components and sensors, progressing from laboratories in many universities to be scaled up in manufacturing facilities across the United States.

Alone, each of these new institutions would be remarkable. The fact that all emerged from this shared experience with the formation of the ISN is a significant marker of successful institutional capacity building. The Army sponsor is also using these institutional models to build new capacity. In 2018, the Army established both a new requirements organization in Army Futures Command, and an Artificial Intelligence Center built on a similar model of university, industry, and government collaboration and expectations for technology transitions.

## **Conclusions and Next Steps**

In conclusion, the technology focused research teams showed patterns of enrollment which enabled the entrepreneurial start-up institute to begin producing results in science, engineering, and technology transitions. The qualitative techniques used by STS scholars Latour and Law to ‘follow of the actors’ illuminated the organizational history

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<sup>82</sup> David Chandler, “New Institute Will Accelerate Innovations in Fibers and Fabrics,” *MIT News*, April 1, 2016, New institute will accelerate innovations in fibers and fabrics.

of the founding of this institute. Through this process, outsider viewers in 2019 could look back at the start of this century and see how these groups of people organized their activities into interdisciplinary teams, and structured their activities to exploit their success and make changes needed. The researchers demonstrated heterogeneous engineering, bringing together people from many disciplinary domains and organizations to create new modes of enrollment and network creation. The nanotechnologies came in varied formats, so the teams as networks of actors demonstrated many approaches with collaborations, competitions, and varying outcomes. Because of the early controversy, interested viewers today can learn what the ISN did nearly 20 years ago, because the Internet Archive captured their early Internet products.

In the next chapters, I will examine three ISN case studies, focused around a different set of networked actors: basic research, applied research, and prototyping. Each case study is aligned with a different type of funding in the Defense budget, and therefore taps into different communities among both Army research sponsors and the ISN researchers. I will identify lessons learned which can be applied by federal S&T managers, other universities seeking to organize and network into similar S&T centers, and members of the public whose tax dollars supported this investment. In 2018, the Army established a new four-star command, called Army Futures Command, which seeks to accelerate transitions from S&T investments in academic and industry partners. The observations from the start-up phase of the ISN can help inform both the formation of the Army Futures Command and the different patterns of behavior which research sponsors and transition accelerators can seek and incentivize to accelerate transitions of technology to achieve their goals.

## Chapter 4.

### 6.1: Basic Research, Enrollment and Translation

#### Overview

In his review of the first three years of the NNI, NSF program manager Mihail Roco described challenges that had confronted nanotechnology since his 1991 interview: "...I said that it might take '5–10 years' for the field to be recognized. One reason was that the nanoscale behavior could not be easily measured, simulated, or controlled."<sup>83</sup> MIT Professor Angela Belcher pioneered science to design, control, and use nature to create new materials with tunable nanoscale properties that could be scaled up to the macroscale. In addition to pioneering new materials, she pushed forward a new academic domain, bioengineering with synthetic biology. Belcher provides a useful case study because, as a new faculty member to MIT when the ISN was being established, she established a set of research endeavors that could be specifically linked with this emerging institution and her new start as faculty. Other ISN scientists and researchers with more time at MIT had more far-flung research partnerships in their own actor networks, so the research endeavors of more mature MIT faculty members are more challenging to interpret solely within the ISN context.

#### Analysis Methods and STS Theory

Many STS analyses of knowledge production in laboratories use qualitative methods, including rich description based on ethnography. As discussed in the

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<sup>83</sup> M. Roco, "The US National Nanotechnology Initiative after 3 Years (2001-2003)," *Journal of Nanoparticle Research* 6, no. 1 (February 2004): 1–9, <https://doi.org/10.1023/B:NANO.0000023243.25838.73>.

introduction, my analytic approach relies on information that is publicly available in 2019, not on in-person observation from the ISN's first contract phase, in years 2002 through 2007. The Internet Archive captures many but not of the all web sites used by the actor network participants to disseminate information and persuade others, both scientific and members of the public, of the value of their research. The value of the Internet Archive is enhanced by the site's **repeated** captures of the same web pages published by an organization or individual, so that changes between observations can be analyzed. My qualitative descriptions seek to outline the activities performed by the Belcher team in the context of the ISN during that first contract period. However, the information is necessarily incomplete. I seek to understand how this actor network produced output that could be observed at the time, by research sponsors and the public, and that can be observed more than a decade later.

To supplement the qualitative analysis, I introduce quantitative analysis techniques based on data science methods, particularly Social Network Analysis (SNA) techniques. Bruno Latour expressed concern about observers confusing the network as externally defined with the networks as enacted by the participants:

“ANT is not about traced networks, but about a network-tracing activity.... there is an actor whose definition of the world outlines, traces, delineates, describes, files, lists, records, marks or tags a trajectory that is called a network.... no tracing is done by an actor exterior to the net. A network is not a thing, but the recorded movement of a thing. ... what moves and how this movement is recorded....”<sup>84</sup>

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<sup>84</sup> Bruno Latour, “On Actor-Network Theory: A Few Clarifications,” *Soziale Welt* 47, no. 4 (1996): 348.

These quantitative methods enabled me to trace the networks as enacted by the participants themselves, in published output that resulted from the research partnering of the actors associated with Professor Belcher. Those publications (listed in Appendix A) provide the baseline for the set of actors, which are then assessed for linkages to the ISN and entrepreneurial start-ups. As Latour cautioned, no tracing was imposed by an external agent: the methodological goal is to trace the paths created by the network actors themselves. This self-assembly of a functioning set of network relationships arose around the scientific challenges of creating nanomaterials using genetic engineering for self-assembly. Clearly this approach privileges those humans who formalized their research relationships sufficiently to produce a scientific article. Certain humans who were essential to the ISN-based research, such as the laboratory manager and nano-instrumentation trainers, are not typically mentioned in scientific articles. Non-humans, such as the abalone snails and the M13 viruses which Professor Belcher and her research team partners worked with, have no direct voice – but prove central in the research publications I examined. In many ways, the collaboration between humans and non-humans is central and is highlighted most strongly in these examples, compared with other research project at the ISN.

### **Development of an Interdisciplinary Scientist**

Angela Belcher practiced extensively interdisciplinary research. A seventh-generation Texan, she earned her bachelor's, master's, and PhD degrees and performed as a post-doctoral fellow at the University of California, Santa Barbara (UCSB). Her growth as an academic provides an example of co-production, with her self-directed research guided by mentors from many academic disciplines. Her undergraduate degree

combined her work in physics, molecular biology and organic chemistry labs into an interdisciplinary degree in Creative Studies. In her undergraduate studies, she took graduate courses in proteins, and saw aquatic abalone snails for the first time. In her 2003 commencement address to the UCSB graduating class, she described choosing to pursue her PhD in a new area, inorganic chemistry. Through her PhD, she studied natural self-assembly: how abalone snails make their shells. The abalones have worked out over millions of years of evolution how to code their genes to combine 2% protein into 98% calcium carbonate – chalk – to build exquisitely detailed self-assembled structures, in seawater, without toxic chemicals used or produced.

For her post-doctoral studies, Belcher shifted to yet another field, Electrical Engineering. Working with UCSB Professor Evelyn Hu, both applied the concepts of biological self-assembly and clean manufacturing as demonstrated by abalones to create new materials for electronic components. Their goal was to produce new materials using genetically programmed self-assembly, which neither consumed nor produced toxic materials – a significant divergence from contemporary electronics production which applies materials to substrates using hazardous chemicals. She and Professor Hu continued their partnership over time, to commercialize their innovations. Then as a new faculty member at the University of Texas-Austin, she sought convergence across her fields of study and interest:

I wanted to combine everything I had learned up to that point... to genetically engineer protein-based viruses to grow and assemble electronic materials to form next-next-generation electronic computers.... That seemingly crazy idea has led to millions of additional dollars in grant

funding, 11 patents, numerous papers, over 20 PhD student projects, starting my own company, a faculty position at MIT, and 500,000 Frequent Flyer miles.<sup>85</sup>

Even as a junior faculty member, Professor Belcher demonstrated tacit knowledge about how to perform effectively in the academic arena. She outlined her research productivity in terms of the metrics used by the Army Research Office and other federal research sponsors: faculty acknowledgements (awards and honors); students graduating (masters and doctoral degrees); and invention disclosures (patents and peer-reviewed publications). In this brief statement, she demonstrated that she had translated herself into a faculty member worthy of continued research investments, even in high-risk novel areas. This approach enabled her to enroll research partners at faculty and student levels, as well as demonstrate her positioning as up-and-coming MIT faculty.

### **Enrolling Partners to Create New Opportunities**

Professor Belcher built awareness both deeply among scientific researchers and broadly among the American public. In the national business media, a 2001 *Forbes* business magazine featured her on the cover of their recurring feature series, the 'next big thing' magazine cover focused on nanotechnology, and in "The Next Small Thing" nanotechnology feature article.<sup>86</sup> In 2002, the *MIT Technology Review* included her on their list of key innovators under age 35. Being included on this list brought her prominence and prestige among more than 1000 MIT faculty members, just as she joined

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<sup>85</sup> Angela M. Belcher, "The College of Creative Studies - Distinguished Alumni - Angela Belcher, PhD, Commencement Speech" (June 2003), [http://www.ccs.ucsb.edu/distinguished\\_alumni/Belcher/](http://www.ccs.ucsb.edu/distinguished_alumni/Belcher/).

<sup>86</sup> Elizabeth Corcoran, "The Next Small Thing," *Forbes*, July 23, 2001, <https://www.forbes.com/forbes/2001/0723/096.html>.

the faculty. In 2002, Belcher also co-founded the startup business Cambrios Technologies with her UCSB Professor Evelyn Hu, to commercialize their biologically-directed production of electronic components.<sup>87</sup> Their initial core technology was transparent electronic materials self-assembled using viruses, which could make production of large flat-screen television and computer displays cheaper, faster, and much less toxic. In the following year, her creative inventiveness would be recognized with a 'Genius grant' as a 2004 MacArthur Foundation Fellow. Her peer recognition for her inventiveness continued, when in 2013 she earned the \$500,000 Lemelson-MIT prize for her innovations as she "genetically engineers viruses to create new products."<sup>88</sup> While *Engines of Creation* author Eric Drexel debated Nobel Prize winning nanoscientist Richard Smalley about whether nanotechnology could advance by self-assembly, arguing top-down versus bottom-up assembly, Professor Belcher simply discovered how to do so, creating nanostructures through directed evolution of viruses.<sup>89</sup>

As a new faculty member at MIT in 2002, Professor Belcher had to communicate her research in order to enroll partners – students, post-doctoral fellows, research partners, and research grant sponsors. The MIT Department of Materials Science and Engineering (DMSE) web site introduced her research focus: "... understanding and using the process by which Nature makes materials in order to design novel hybrid organic-inorganic electronic and magnetic materials on new length scales."<sup>90</sup> She taught

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<sup>87</sup> "About Cambrios," September 28, 2007, <https://web.archive.org/web/20070928041813/http://www.cambrios.com/39/Company.htm>.

<sup>88</sup> *Angela Belcher, 2013 Lemelson-MIT Prize Winner*, 2013, <https://youtu.be/LeFRnNostsY>.

<sup>89</sup> Ray Kurzweil, "The Drexler-Smalley Debate on Molecular Assembly," December 1, 2003, <http://www.kurzweilai.net/the-drexler-smalley-debate-on-molecular-assembly>.

<sup>90</sup> MIT Department of Materials Science and Engineering, "DMSE Faculty: Angela Belcher," December 26, 2002, <https://web.archive.org/web/20021226221928/http://dmse.mit.edu/faculty/faculty/belcher>.

introductory courses to undergraduates, and did outreach activities with the ISN and the local community at the Boston Museum of Science. In order to translate her knowledge and create new capacity for fellow researchers to join her researcher, Professor Belcher had to both enroll others and translate her knowledge, while allowing research partners to translate their knowledge in this new domain back to her.

### **Enrolling Fellow Scientists**

The broader public awareness of Professor Belcher's research was catalyzed by novel discoveries disclosed through scientific articles in top-ranked journals. In 2002, Professor Belcher and fellow nano-biotechnology pioneer NC Seeman described their biology-inspired nanotechnology self-assembly techniques, which was published in the *Proceedings of the National Academy of Sciences*.<sup>91</sup> This article sought to inform and enroll a broader scientific audience about the potential for using techniques analogous to genetically-programmed techniques animals used to create exquisitely structured organic-inorganic compounds with desirable material properties. This article built on a set of articles Belcher published with fellow researchers in *Science* and *Nature*, introducing novel approaches to genetically engineered self-assembly of new materials. A 1999 *Nature* article described the results of research on biological self-assembly resulting from Doctor Belcher's analysis with a team of researchers studying organic-inorganic materials created by abalone snails, and other protein-mediated biomolecular composites including spider silk.<sup>92</sup> Her PhD work extending biomolecular self-assembly to electronic

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<sup>91</sup> N. C. Seeman and A. M. Belcher, "Emulating Biology: Building Nanostructures from the Bottom Up," *Proceedings of the National Academy of Sciences* 99, no. Supplement 2 (April 30, 2002): 6451–55, <https://doi.org/10.1073/pnas.221458298>.

<sup>92</sup> Bettye L. Smith et al., "Molecular Mechanistic Origin of the Toughness of Natural Adhesives, Fibres and Composites," *Nature* 399 (June 24, 1999): 761.

components that could be useful for semiconductor-based electronics was documented in a 2000 *Science* article.<sup>93</sup> This work proved fruitful as the basis for both research and marketable products and processes. A 2002 *Science* article described the interdisciplinary application of her research into biologically directed materials self-assembly, using liquid crystals to create molecular wires by positioning quantum dots using viruses.<sup>94</sup> All these innovations derived from the techniques Professor Belcher and her research partners used to genetically engineer specific viruses. The virus chosen was the M13 bacteriophage, a virus that consumes parts of a specific bacteria. These new variations emulated patterns discovered in abalones. The snails combine readily available environmental materials and use genetically programmed self-assembly to build strong, tough structures from calcium variants adhered with proteins. As Professor Belcher related on many occasions, she wanted to extend the virus combinations to the rest of the periodic table of elements. Her later collaborators genetically modified M13 viruses to be attracted to other elements on the periodic table beyond calcium, such as zinc sulfide (ZnS). This breakthrough approach used viruses in self-ordering systems to create nanocrystals with tunable optical, electronic, and ionic properties – for electronics, solar energy, cancer fighting, and other uses.

### **Enrolling Army Research Sponsors**

Even before she was on-site at MIT as a member of the faculty, Professor Belcher was listed as an ISN participating faculty member: expectations were high. To the outside

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<sup>93</sup> Sandra R. Whaley et al., “Selection of Peptides with Semiconductor Binding Specificity for Directed Nanocrystal Assembly,” *Nature* 405, no. 6787 (June 2000): 665–68, <https://doi.org/10.1038/35015043>.

<sup>94</sup>S.-W. Lee et al., “Ordering of Quantum Dots Using Genetically Engineered Viruses,” *Science* 296, no. 5569 (May 3, 2002): 892–95, <https://doi.org/10.1126/science.1068054>.

observer, involvement in the ISN research portfolio provided her not only research partnerships, but also funded her research projects. Emboldened by the potential of the ISN, in January 2003, the Army Research Office decided to establish another University Affiliated Research Center (UARC), a complement to the ISN focused on biotechnologies. The addition of biotechnology to nanotechnologies aligned with the NNI focus on nano-bio-info-cognitive convergence, which increased in importance over time.<sup>95</sup> The Army Research Office announced the competition for the Institute for Collaborative Biotechnologies (ICB), held site visits in California and Maryland, and awarded the contracts, all in 2003.<sup>96</sup>

In contrast to the ISN's single-university structure, the ICB combined three universities to research bio-inspired materials and networks. UCSB was the lead university, with the California Institute of Technology (CalTech) as one subcontractor. The other subcontractor university team was MIT, led by Professor Belcher. As the ICB enrolled scientists, the new institution also enrolled Army research sponsors, including Congressional funders. By packaging research investments into significant and notable research institutions, Army research sponsors gained prestige and built out their own research networks. These networks extended to members of the Army's own internal S&T community, and created new opportunities for Army scientists to collaborate with Professor Belcher and other participants in the ISN and ICB. In addition, the co-location of two leading-edge UARCs enabled many Army and Defense visitors, including senior

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<sup>95</sup> Bainbridge et al., *Managing Nano-Bio-Info-Cogno Innovations*, 2006.

<sup>96</sup> US Army Research Office, "ARO Solicitation: Broad Agency Announcement DAAD19-03-R-0005 for The Army Institute for Collaborative Biotechnologies," FedBizOpps.Gov, January 3, 2003, [https://www.fbo.gov/index.php?s=opportunity&mode=form&tab=core&id=11a6a17957ade74894af8d3c6e31e076&\\_cvview=0](https://www.fbo.gov/index.php?s=opportunity&mode=form&tab=core&id=11a6a17957ade74894af8d3c6e31e076&_cvview=0).

military and civilian leaders and attendees in the military senior service colleges, discuss and learn about Defense-funded research.<sup>97</sup>

The outside viewer could intuit the network connections provided by Professor Belcher, bringing together her academic advisors at UCSB. She demonstrated strong network relationships by traveling to an ICB university partner with her 2011 TED Talk on “Using Nature to Grow Batteries” at TEDx CalTech.<sup>98</sup> One could infer linkages between proposals for the ISN competition and the rapid ICB competition. Like the ISN, the ICB performed sufficiently well for their five-year research contracts to be renewed by the Army Research Office sponsors. Favorable reports on the productivity of the research were briefed to Congress, as part of the annual budget hearings. For both research centers, funding priorities did change after the initial five-year contracts, adapting to successes and new needs. From the view of tracing the impact of the Actor-Network around Professor Belcher, having a second major Defense-funded strategic research institution established in short order, tailored to the skill set that Professor Belcher was pioneering, suggests another aspect of translation of her methods to train many other researchers and support many other research projects.

### **Qualitative Translation in Basic Research**

The significant level of innovation demonstrated by Professor Belcher required her to demonstrate both translation and enrollment. For basic scientific research, scientists

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<sup>97</sup> Industrial College of the Armed Forces (ICAF), “Biotechnology Industry Study 2009” (Fort McNair, Washington, DC: National Defense University, May 2009), <https://es.ndu.edu/Portals/75/Documents/industry-study/reports/2009/icaf-is-report-biotechnology-2009.pdf>.

<sup>98</sup> Angela Belcher, *Using Nature to Grow Batteries*, TEDx CalTech, 2011, [http://www.ted.com/talks/angela\\_belcher\\_using\\_nature\\_to\\_grow\\_batteries](http://www.ted.com/talks/angela_belcher_using_nature_to_grow_batteries).

may not see the impact of their fundamental work for years, or even decades. Assessing the impact of such work in a short timeframe can be challenging. Using qualitative analysis, the Actor-Network can show capacity created for further knowledge creation. In this measure, seeing knowledge built on knowledge suggests mutual benefit from making the original investment in supporting the research. Translations to allow influence at a distance are crucial. People who are trained in the discoveries, techniques, and potential applications can carry basic research forward in a variety of ways. Inscriptions such as published articles in journals and migration of Belcher-trained scientists to universities around the world can catalyze ongoing research.

### **Detecting Translation**

The scientific translation function of enabling ‘action at a distance’ can be difficult to discern or to visualize. The challenge is increased with novel, interdisciplinary research: which disciplinary communities are tracking the new discoveries? In addition to being involved with the ISN and ICB, Professor Belcher and fellow ISN faculty Professor Linda Griffith were also involved in MIT’s efforts to stand up the Department of Biological Engineering (<http://be.mit.edu>), with new research areas of computational biology and synthetic biology. The establishment of a new department to extend this new scientific discipline provides externally visible indicators of translation. This translation would continue into the future, as new scholars graduated with advanced degrees in bioengineering and advanced new material development using biology. A key Army officer who attended MIT for graduate education, Major Luis Alvarez (discussed in Chapter 6), also extended the translation as an MIT alumni by establishing a bioengineering course of study at the US Military Academy at West Point.

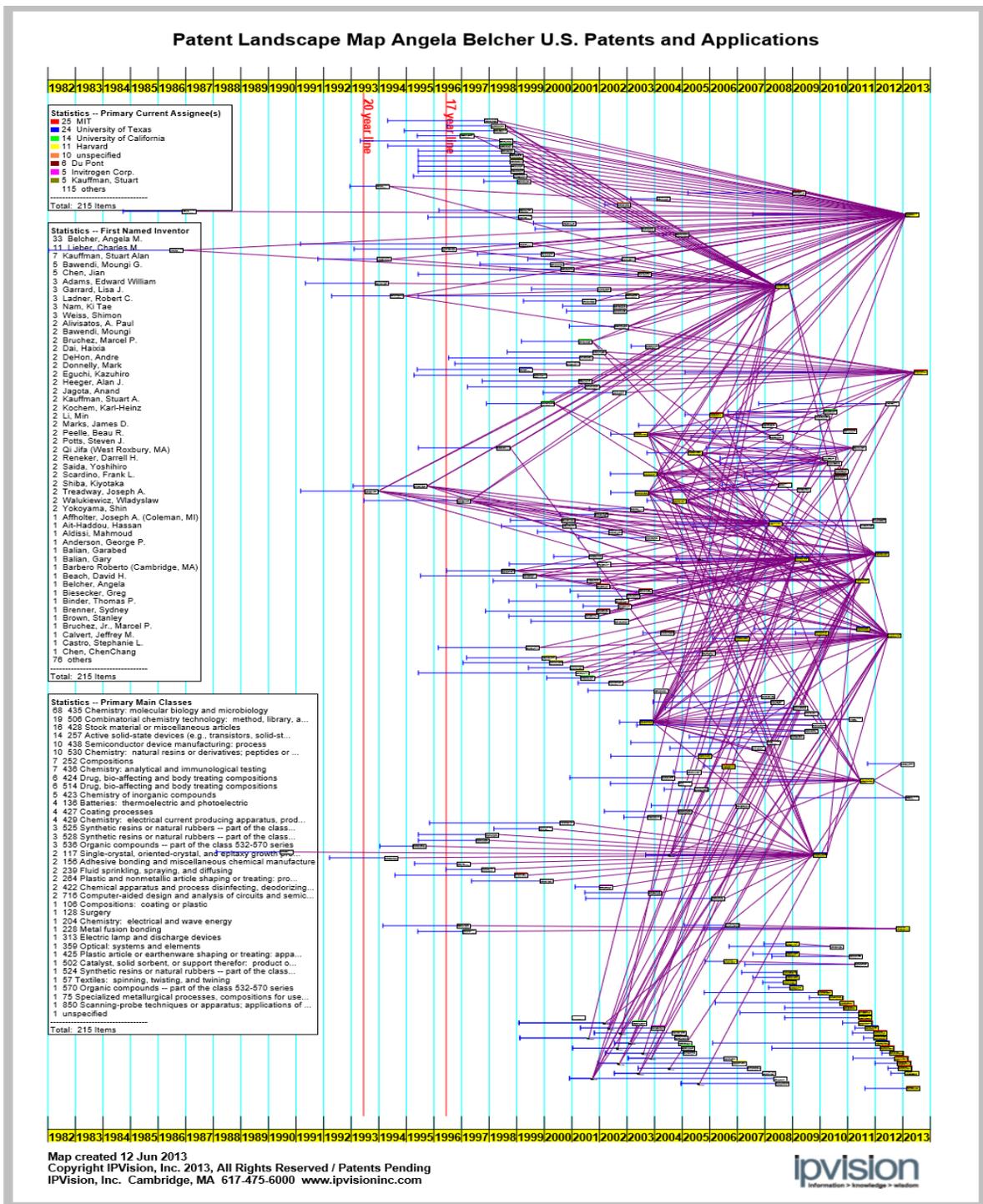


Figure 15. Patent Landscape Map: Angela Belcher, US Patents and Applications, by IPVision.com, 12 June 2013. (See Fair Use Determination)

<sup>99</sup> IPVision.Com, "Patent Landscape Map: Angela Belcher U.S. Patents and Applications" (June 12, 2013), <http://leemison.mit.edu/sites/default/files/content/documents/awards/Patent%20Landscape%20Map%20of%20Angela%20Belcher%20Inventions.pdf>.

In addition to helping establish new academic enterprises, translation was also demonstrated by the fact that Professor Belcher's patents were cited and licensed by individuals, teams, and firms around the world. Although some information around intellectual property is sensitive and not disclosed, organizations such as IPVision provide proprietary software to track patents. The MIT-Lemelson award granted in 2013 showed an image of the map of patents affiliated with Professor Belcher (see Figure 15). These patent maps show 'inheritance' of intellectual property, so enable interested researchers to see linkages and generative outcomes of patent-documented innovations.

Even without the underlying proprietary information held by the company, the visual image of this patent map reveals how sparse the patent domain was, prior to Professor Belcher's submissions. Few patents relevant to Professor Belcher's work were shown before the 1993 20-year line or the 1996 17-year line. (These times are significant, showing the expiration period for unrenewed patents awarded during these time periods.) Reading the patent map as a timeline, from left to right, shows how far into the future these seminal scientific discoveries can influence other scientific researchers. Over time, this intellectual property 'white space' is populated with submissions, indicated in blue lines, showing the time between submission and patent award. Patent awards are noted with boxes; the lower left corner of the boxes naming the patent and first inventor shows date of award. Translation is visually indicated by the purple lines, which show other people citing the patents submitted by Professor Belcher and other researchers in this new domain. Stabilization of the network is reinforced when people follow the research closely enough to build on existing knowledge. In this way, the image suggests how certain patent-producing actors can fill the Actor-Network role of being points of passage

which future creators are obliged to acknowledge publicly. The new researchers who would build on this patented research, or related research which is not patented, need to consult either in person or through published materials on how to extend the science by building on these discoveries and creations. Acknowledgement of prior art in patents and articles was seen as central to the practice of science and technology innovation.

## Quantitative Analysis of Actor Networks

Despite the detailed information on who participates and what notice is generated outside of the research group, indicating the potential capacity of the group as a whole, the qualitative analysis of the historical observer does not provide insight into the details of whose relationships were most salient inside the Actor Networks being explored. The details of how individual researchers split up the laboratory tasks between synthesizing molecules, growing healthy batches of bacteriophages, computing potential organic-inorganic compounds that could work, and modifying the protein coats on viruses to be coated with metal to transmit electrons are not discernable by the outsider. There are suggestions of how certain networks touch and overlap other networks, but these linkages are not clear. Even the patent map, which visually appears to be a social network, is actually only an annotated list. Given the inability to reach back in time to gain details that would be helpful for qualitative analysis, quantitative analysis may provide other avenues to gain insight into how these actor networks actually worked.<sup>100</sup> Using quantitative techniques based on Social Network Analysis methodologies may illuminate who worked

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<sup>100</sup> Michael J. Prietula, Kathleen M. Carley, and Leslie George Gasser, eds., *Simulating Organizations: Computational Models of Institutions and Groups* (Menlo Park, CA: AAAI Press/MIT Press, 1998).

most closely with whom; what were the results; and what those network relationships can show about the early days of interdisciplinary research at the ISN and beyond.

### **Challenges in Evaluating Basic Research**

This challenge of lack of visibility into research by outsiders affects not only historical viewers, but also concurrent partners trying to assess the research. Federal and Defense scientific research sponsors and program managers spend substantial time and energy attempting to assess, accelerate, and translate outputs of funded research into Defense-relevant applications. A major complication in tracing basic research in terms of output is that each basic research finding can have applications in a wide array of fields and products. When is the material 'done'? As discussed in chapter 3, the exact same nanomaterial in a test tube can be either a complete capability, or used as part of another capability. For Professor Belcher's group, an example of this degree of capability was the organic/inorganic compounds used in flexible displays, which required five years to mature for commercialization. The same nanomaterial in a beaker could be foundational for other nanomaterials, either as a product or as a process (virus-based rapid materials evolution or layer-by-layer soft lithography). Since direct results take time and can affect a broad swath, for basic research, creating the capacity for further innovation matters.

The decades-old interdisciplinary practices of analyzing social networks and connections continued to increase in use and applications through the period of this study, accelerated by the ubiquity of powerful computing and ability to store and correlate entity data at speed. Analytics that were previously intractable for large datasets became usable by researchers who lacked access to supercomputers. The quantitative analyses enabled researchers to understand subtle distinctions between people and their influence within

their networks.<sup>101</sup> Using quantitative techniques from Social Network Analysis to trace the actors – people, products, publications – allows for statistically-based assertions to be made about the relative importance of specific participants to each other, using measures such as centrality and betweenness (which will be explained later in this chapter and detailed in Appendix A).<sup>102</sup>

While qualitative analysis can provide specific and textured details, I argue that quantitative analysis can amplify the weak signals found in early-stage ventures, in both research and business, potentially enabling investors to differentiate where an equal amount of resource input might have a greater potential impact. The resource changes could be more talent or expertise; access to new equipment; or reduction of administrative obstacles that consume resources. Importantly, key resource mobilization can occur with extension of networks to include new actors.

The quantitative assertions resulting from analysis can then be assessed using qualitative analysis of what can be seen in the world. The observer who was not involved in the research may get a sense of what was done; how activities occurred; and which potentially productive networks could create more innovations. By augmenting qualitative **descriptions**, those internal and external actors seeking to accelerate technology transitions can use the quantitative analytic measures as **diagnostic** tools, finding avenues to connect actors across the networks to create purposeful pathways toward transition. (Potential future extension into **predictive** analytics should carefully consider what information was not available, to understand areas of uncertainty and risk.)

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<sup>101</sup> Ithiel de Sola Pool and Manfred Kochen, "Contacts and Influence," *Social Networks* 1, no. 1 (January 1978): 5–51, [https://doi.org/10.1016/0378-8733\(78\)90011-4](https://doi.org/10.1016/0378-8733(78)90011-4).

<sup>102</sup> Steven H. Strogatz, "Exploring Complex Networks," *Nature* 410 (March 8, 2001): 268.

## Identifying the Actor Network

The necessary first step in applying Social Network Analysis techniques is to define the actor-network of interest. As Latour stated, the actors trace their own networks, and the analysts must follow those traces. To start, the network should be assessed to determine what actors are exogenous, or outside of a given network analysis focused on a specific issue. In this instance, my analysis is interested in researchers affiliated with Professor Belcher on biotechnology research during the start-up phase of the ISN. Data is drawn from the now-defunct BiomedExperts web site, which claimed to be the first literature-based scientific social network and was created to increase biomedical research

Computed Network	Publications	Coauthors	2nd Level	3rd Level	Level 3 Increase	
<b>Langer, Robert S</b>	8 Feb 2009	<b>424</b>	<b>348</b>	<b>11,269</b>	<b>243,421</b>	<b>8.1%</b>
	8 May 2009	<b>437</b>	<b>361</b>	<b>12,402</b>	<b>263,100</b>	
<a href="http://www.biomedexperts.com/start/PersonDetailPage.aspx?pid=774465">http://www.biomedexperts.com/start/PersonDetailPage.aspx?pid=774465</a>						
<b>Cima, Michael J</b>	8 Feb 2009	<b>27</b>	<b>23</b>	<b>980</b>	<b>31,510</b>	<b>66.5%</b>
	8 May 2009	<b>28</b>	<b>25</b>	<b>1,519</b>	<b>52,463</b>	
<a href="http://www.biomedexperts.com/Start/PersonDetailPage.aspx?pid=245237">http://www.biomedexperts.com/Start/PersonDetailPage.aspx?pid=245237</a>						
<b>Hammond, Paula T</b>	8 Feb 2009	<b>33</b>	<b>27</b>	<b>686</b>	<b>22,931</b>	<b>7.0%</b>
	8 May 2009	<b>35</b>	<b>28</b>	<b>714</b>	<b>24,535</b>	
<a href="http://www.biomedexperts.com/Start/PersonDetailPage.aspx?pid=523678">http://www.biomedexperts.com/Start/PersonDetailPage.aspx?pid=523678</a>						
<b>Belcher, Angela M</b>	8 Feb 2009	<b>20</b>	<b>26</b>	<b>379</b>	<b>8,508</b>	<b>11.6%</b>
	8 May 2009	<b>21</b>	<b>28</b>	<b>440</b>	<b>9,499</b>	
<a href="http://www.biomedexperts.com/start/PersonDetailPage.aspx?pid=99044">http://www.biomedexperts.com/start/PersonDetailPage.aspx?pid=99044</a>						

Figure 16. Computed social networks based on publications of four MIT professors who research biotechnology at the ISN (from BiomedExperts.com, 2009).

collaborations.<sup>103</sup> (This type of functionality was later integrated into the Google Scholar search engine, <http://scholar.google.com>, among other academic research focused Internet search engines.) The table in Figure 2 below shows publication statistics of four MIT professors who conducted biotechnology research at the ISN in this period, given the

<sup>103</sup>Internet Archive.org, "BiomedExperts.Com," August 2, 2009, <https://web.archive.org/web/20090802101153/http://biomedexperts.com/>. (Note that the top-level BiomedExperts.com domain was captured on the Internet Archive, but not the underlying database information.)

delay after research for publications to be released (up to two years from research activity to peer-reviewed publication). From these publication statistics, the initial social networks can be computed. This sample from February 2009 to May of 2009 shows numbers of publications for Professors Langer, Cima, Hammond and Belcher, and the rate of change for each. The number of coauthors is listed, as well as the coauthors' coauthor connections ('friend-of-a-friend' second level or degree connections), as well as the coauthors' coauthors' coauthor connections ('friend-of-a-friend-of-a-friend' third degree connections).

The chart shows the benefits of being well-known. Key leaders 'get bigger faster,' with large third-degree links to scientific publication co-authors. Following the social network theory of the strength of weak ties, presumably these third-degree links can be leveraged to do research, learn from related research, exchange student researchers, or otherwise exploit their extended relationships.<sup>104</sup> MIT Professor Robert Langer clearly dominates in this research domain, with the site capturing over 400 of his publications involving more than 360 co-authors. He published significant scientific papers for longer than his co-authors in this chart, and his success attracts emerging talent to research with him, resulting in more papers. His co-authors are themselves prolific, leading to a second-degree link to more than 12,000 co-authors and third-degree links to more than a quarter million scientific authors. Such a massive base is hard to increase greatly, so Professor Langer's social network as captured by this site shows eight percent growth in third-degree links in three months. An example of leveraging these extended linkages was

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<sup>104</sup> Mark Granovetter, "The Strength of Weak Ties," *American Journal of Sociology* 78, no. 6 (May 1973): 1366, <https://doi.org/10.1086/225469>.

demonstrated by Professor Michael Cima. He joined the MIT faculty in 1986, so in this era was a seasoned MIT faculty member. Cima co-founded a company with Professor Langer, and illustrates the value of linking with highly prolific co-authors, leading to a substantial increase in third-degree links totaling 66.5 percent. Similar raw numbers of third-degree links were shown by Professor Langer, because the two authors shared the same third level networks. Here again the ability of additional investments to influence Professor Cima's future research and business ventures will be somewhat diluted in the context of the prior investments.

In contrast, Professor Angela Belcher was an up-and-coming researcher in biotechnology, new to MIT faculty, recognized with a MacArthur 'genius' grant for her innovative approaches, and increasing in publication-based third-degree network links over ten percent in this interval: she and her cohort are growing at a faster rate, even though the absolute numbers of publications are not yet large. An investment by a research sponsor in this up-and-coming researcher could have the same positive impact as a venture capitalist funding an entrepreneurial start-up company. Since the Defense research sponsors were being pushed to act more like venture capitalists, creatively investing in scientific research to accelerate technologies for transition, research sponsors would seek this type of high-leverage investment for their funding.

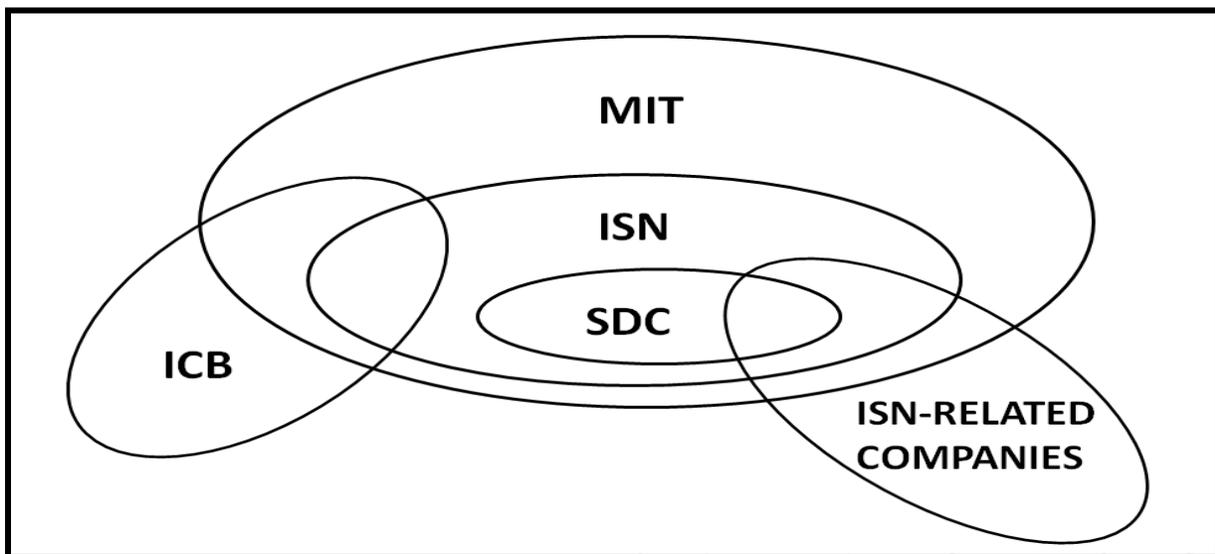
Since his social networks are so large, with third-degree networks including hundreds of thousands of researchers, Professor Langer's momentum is harder to influence with strategic investments funding either research or entrepreneurial start-ups. Investors seeking to fund either research or business formation might seek other options, backing scientists who can be more influenced by a single investment. Of this group,

Professor Belcher begins this research interval with third-degree research publication links to 8500 researchers, and ends three months later with nearly 1000 added third-degree links. Compared with Langer, Belcher's 'Langer ratio' (her third-degree publication computed network compared with Langer's in this period) improved from 28.6:1 in Feb 2009 to 27.7:1 in May 2009. Cima's 'Langer ratio' moved from 7.7 to 5.0 in this interval, reflecting similar raw numbers of third-degree authors as Langer, since both share these network links. Professor Hammond's moved from 10.6 to 10.7, showing more publications with relatively fewer new co-authors. The 'Langer ratio' I computed highlights subtle differences in the *rate* of change, which would be more difficult to determine based only on raw numbers of publications in this period. These quantitative measures amplify weak signals that are typical of early-stage endeavors. Since Belcher's 'Langer ratio' showed more change than Professor Hammond's, and offers more opportunity to move, strategic investments in her research and entrepreneurial companies could be expected to have a greater relative impact than investments in the more established authors. The larger 'Langer ratio' may be interpreted as a signal of quality in research partnership: a researcher who links with other prolific researchers could be savvy in partnering with sought-after research partners. For venture funders, Professor Belcher offers investors opportunity to have a greater relative impact, as early money supporting her research and/or the related entrepreneurial start-up businesses.

Key thought leaders demonstrate benefits of extended social networks as they build their scientific reputations over time. Professor Langer's prolific publication network brings talented people to work with him, in research, publications, and co-founded companies: success breeds success. However, investors in scientific research, both

private equity venture capitalists and public research sponsors such as Army and DARPA project managers, need to identify and invest early to shape the direction of future capabilities. Their challenge: how can emerging scientific leaders be identified and capacity to create new knowledge identified early? The network of interest gets overshadowed when Professors Langer and Cima are included without filtering the aspects of interest in this analysis, to focus on very early-stage innovation.

### Tracing the Actor Network



*Figure 17. Analysis Target: The intersection of networks of biotechnology researchers at MIT, related to the ISN, ISN-related entrepreneurial companies, Soldier Design Competition (SDC), and MIT branch of Institute for Collaborative Biotechnologies (ICB).*

In order to focus on the network actors of interest in this biotechnology-focused network analysis, I defined the populations as belonging to core groups associated with the ISN, as shown in Figure 3. (Technical details for this quantitative methodology are provided in Appendix A.) Initially I used standard tools from the UCINET application, to understand the network and demonstrate usability of the tools for entity network characterization. This social network represents a small set of individuals who belong to

multiple groups: biotechnology-focused researchers and entrepreneurial business founders who are also affiliated with the Army-funded ISN at MIT. Co-authors of academic papers who could potentially co-found small businesses with these primary investigators are included, as are ISN-related small business start-up ventures.

My data curation used open, unclassified searches of the public Internet using Google, starting with a set of biotechnology research publications published by Professor Belcher. Using the co-authors as the seed of the network, other lists of people involved in ISN research, ISN-related entrepreneurial companies including from the Soldier Design Competition, and the MIT branch of ICB were compared and correlated for the number of connections between each actor in the resulting mapped social network. Publication co-authors, including Cima, Langer, and Hammond, are mapped, with entities at the intersections of other networks described. Of special interest are those MIT student-entrepreneurs who have multiple links to ISN, biotechnology research, and the prototyping ISN Soldier Design Competition. These highly-engaged entrepreneurial actors already demonstrated interest and capacity in translating concepts into innovative real-world technologies. Clearly these individuals participate in many networks. My analysis focused on the intersection shown in Figure 3 to identify investment inflection points.

For the purposes of this study, initially 56 actors, called egos in Social Network Analysis, were defined at the intersection of these related and overlapping networks. Isolated nodes on the periphery were removed from the original larger dataset, so the resulting network dataset reflects the core of the larger, more diffuse network (essentially, focusing on the 'two-hop' network structure). To begin, I used UCINET social analysis

software for initial visualization and statistical analysis.<sup>105</sup> Based on its improved algorithms, speed, and scalability, I also used SocNetV open source statistical analysis and network visualization software for the remaining analytics.<sup>106</sup>

The UCINET network diagram in Figure 4 graphically displays the connections between each ego (person, group, or organization), with the connected egos. In this mathematical graph, egos (actors) are shown as nodes, and relationship connections are edges linking the egos. Red-colored nodes are connected to single nodes, as a student to a professor might be. Blue nodes indicate triads, with multiple nodes connected to each other. Black nodes indicate the network cutpoints, where boundary spanning actors link substantial parts of the network to the rest of the network.<sup>107</sup>

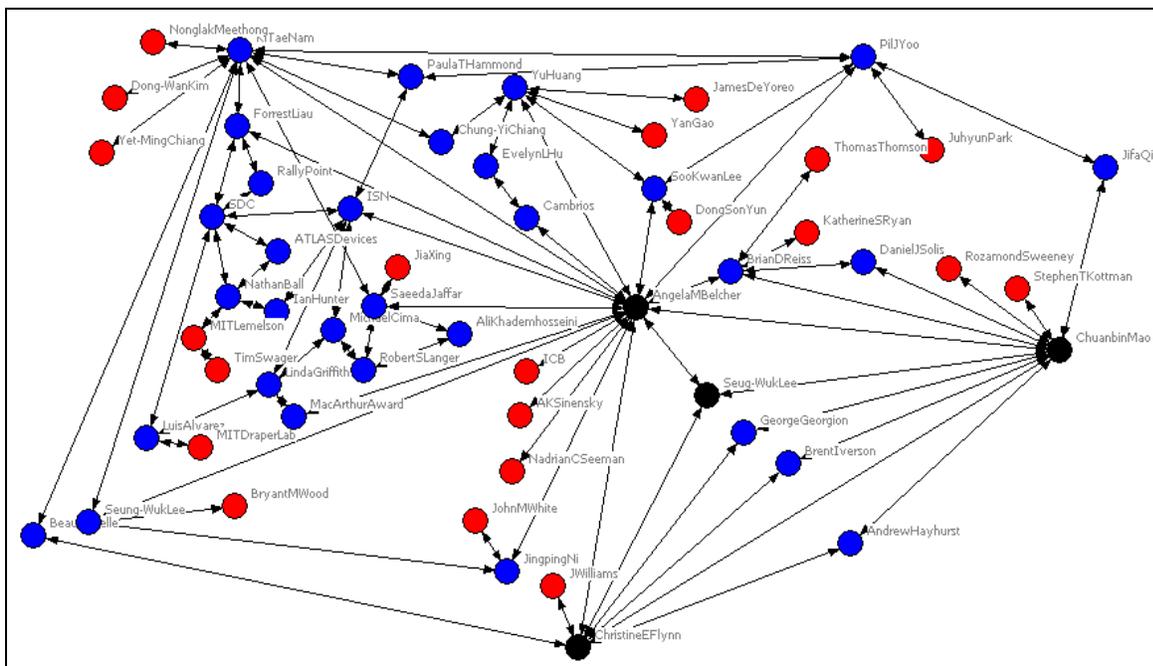


Figure 18. UCINET Network graph with cutpoints in Black (hierarchy clustering from Angela Belcher).

<sup>105</sup> S.P. Borgatti, M.G Everett, and L.C. Freeman, *UCINET for Windows: Software for Social Network Analysis* (Harvard, MA: Analytic Technologies, 2002), <https://sites.google.com/site/ucinetsoftware/home>.

<sup>106</sup> Dimitris Kalamaras, *Social Network Visualization (SocNetV)*, 2018, <https://socnetv.org/>.

<sup>107</sup> Carter T. Butts, "Social Network Analysis: A Methodological Introduction," *Asian Journal of Social Psychology* 11, no. 1 (March 2008): 13–41, <https://doi.org/10.1111/j.1467-839X.2007.00241.x>.

The first look at this network diagram shows the formal, externally observable, public connections documented in selected academic publications linked with Professor Belcher (listed in Appendix A), publicly-funded research, and entrepreneurial business connections of Belcher's co-authors. Only publicly accessible documents were used, so no grant proposals or non-public business links were included: this network analysis considers only overt links. The classic academic connection of one professor as single focal node for several individual students presents several one-way links connected to the same node, suggesting an academic hierarchy. Some of these sub-groups may evolve into co-founded entrepreneurial businesses.

This dataset is constrained to focus on public relationships. Private or proprietary information, such as grant proposals, does not figure into this dataset. Researchers may have shared lab space, equipment, or materials, forging deep relationships that cannot be seen externally. Natural social connections that exist, such as friendship or roommate connections, that are not documented in publicly accessible Internet queries are not included in this analysis, in order to respect concerns about privacy. Similarly, membership networks such as LinkedIn and Facebook may illuminate social connections, but are also excluded based on privacy issues. An on-site, embedded researcher who had obtained informed consent from the participants could have a deeper insight into how other aspects of their interactions shaped the public results of research, publications, technologies transitioned, and business partnerships. Future researchers may find appropriate means to understand these private relationships, which could further illuminate understanding of which relationships contributed to or hindered these ventures.

More detailed analysis of the publication data showed that the name of one author, SW Lee, was erroneously represented in two spellings: Seug-Wuk Lee, and the correct Seung-Wuk Lee. The volunteer who curated the source archive in the early 2000s did not have access to Google Scholar, created in 2004, or the now widespread Digital Object Identifier (DOI) system, to verify the correct spelling. Resolving both names to a single entity, Seung-Wuk Lee, reduced the number of actors to 55 and brought previously secondary relationships into greater prominence. This validated network will be discussed in the quantitative analysis section which follows.

## **Quantitative Analysis**

The UCINET key metrics I initially used to characterize this network do not allow for ready understanding of the most subtle nuances of the connectivity of the actors. Part of this is based on the mathematical challenge of a software program computationally tracking so many links. For this 55-actor network graph, a dense network with directed ties could approach ( $55 \times 54 = 2970$ ) connections. The updated SocNetV software provides scalability capable of analyzing this many social ties, as well as performing millisecond-speed rapid analysis of key network metrics, which enable the observer to discern structure and relative closeness and importance on the information flows between the network actors. The ability to continue to change visibility and assess statistics for various types of quantitative measures was strongly implemented in the SocNetV 2.4 software version, allowing analysts to pivot from query to query to explore the network in detail from a variety of perspectives.

As shown in the mathematical graph of the degree centrality in the Belcher network below in Figure 5, reducing the original network to its core (2-hop network) places many

core network actors into the periphery, connected with each other by only one or two connections. These relationships are important, but not reinforced by repeated collaborations, within this network, in this time period, based on the publications reviewed. Although the map is not equal to the full-life reality of these relationships, these tracings of the network can provide insights. In practice, the central actors in this network which may impact the other actors the most, and translate the science most effectively, are the core actors with many linkages. The computer algorithms built into the SocNetV analytic software enable detailed comparisons and quantitative analysis of the roles of the central, non-periphery actors in this network. I will highlight the key centrality measures to identify the most impactful actors in this network in this period.

Reflexively, in addition to showing the results of my analysis of this social network, in this chapter and Appendix A I provided details to enable other analysts to reproduce my analysis. I intend to enable others to extend these methods to other actor networks.

### The Belcher Network Including 55 Actors

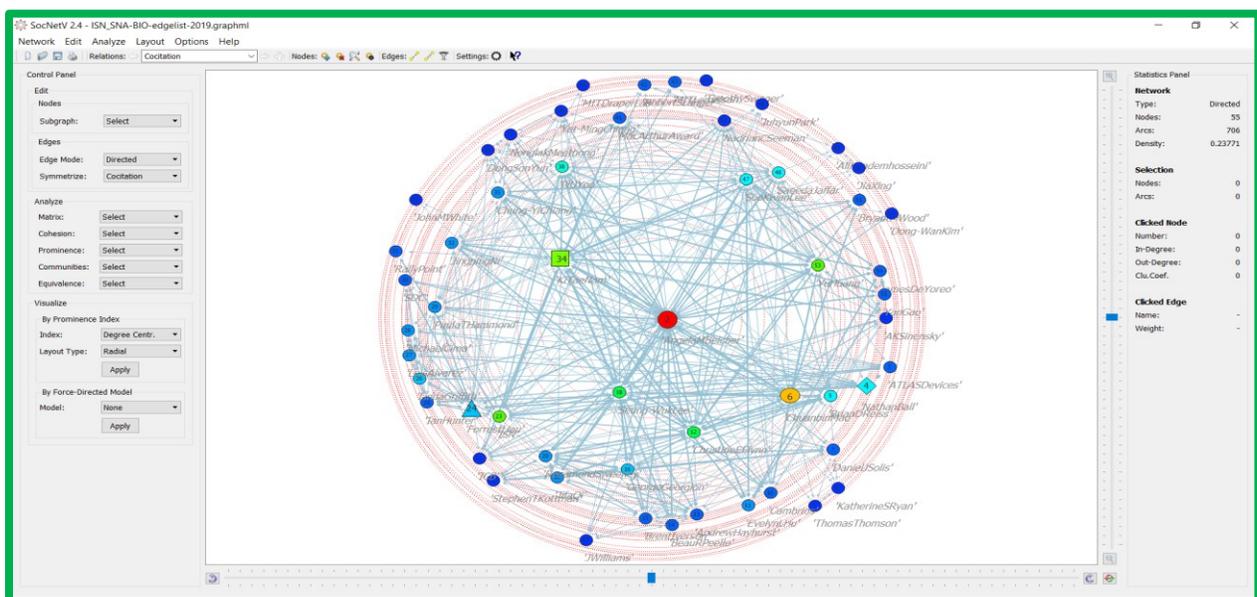


Figure 19. Degree Centrality in the Belcher-Central ISN Network (created with SocNetV, 2018).

## Centrality Measures in the Network

As shown in Figure 5, created with SocNetV, this Belcher-central ISN social network is a strongly connected directed network, with 55 nodes, 706 arcs, and a density of 23.77%. Key factors which can be assessed quantitatively to inform understanding how the network functions include structure of the subgroups, and influence prominence measures from many different angles. Degree Centrality measures each actor's inbound node links: for each actor, 'who links to me?' PageRank Prestige measures the importance of the actors linked with each actor. Essentially, for each node, the number of links are counted; and each inbound link is normalized by the number of its own outbound links. This iterative measure for each actor highlights potential reach to a group of important actors: 'who are the important friends (links) of my friends (links)?' Influence Range Closeness Centrality measures the impact of each actor onto other actors, as an outbound impact measure: for each actor, 'who can I reach with my influence?' Each of the prominence measures assesses different

My analysis highlighted the influence of different pairs of actors in the hierarchy of this network. For the faculty, after understanding the external impact of longer-performing faculty Langer, Cima, and Hammond, Professors Belcher and Griffith were central to these biotech research activities for this network. Among MIT master's students who were also involved in the Soldier Design Competition, Forrest Liao and Nathan Ball proved influential. At the post-master's level, MIT doctoral student Ki Tae Nam demonstrated a similar degree of influence as demonstrated by post-doctoral fellow Chuanbin Mao and doctoral student Seung-Wuk Lee while both researched with Professor Belcher on engineering viruses to create nanomaterials at the University of Texas-Austin. Christine

Flynn also had a high degree centrality as she earned her PhD with Professor Belcher in Texas, then transitioned to MIT to start-up the Belcher Lab as a post-doctoral fellow. The quantitative analytics enable observers to discern which actors displayed these subtle structural equivalencies within the network. In the following sections, I will highlight the key measures and analyze what the quantitative measures suggest about the potential ability of actors in the network to have real-world impact. (Appendix A provides more detail on these quantitative analytics.)

### ***Subgroup Structure***

Unlike typical Internet networks which show an actor distribution of a few very large nodes, with many small nodes, the relative equivalencies of this early-stage research network make differences in personal impact difficult to discern in the structure. The clique census identifies subgroups of actors who are all directly connected. As shown in the dendrogram in Figure 6, this network has 30 cliques where the 55 actors are arranged in different subgroups. The smallest clique consists of 2 actors; the largest includes 30 actors; and the mean includes 6.7 actors. Even without the details to identify each actor, the clustering dendrogram diagram visualizes how similar in size and shape the subgroup cliques are – and therefore how challenging to differentiate impact of the different actors on the network. To clarify, other quantitative measures of prominence will be used to analyze the differences in impact by the central actors.

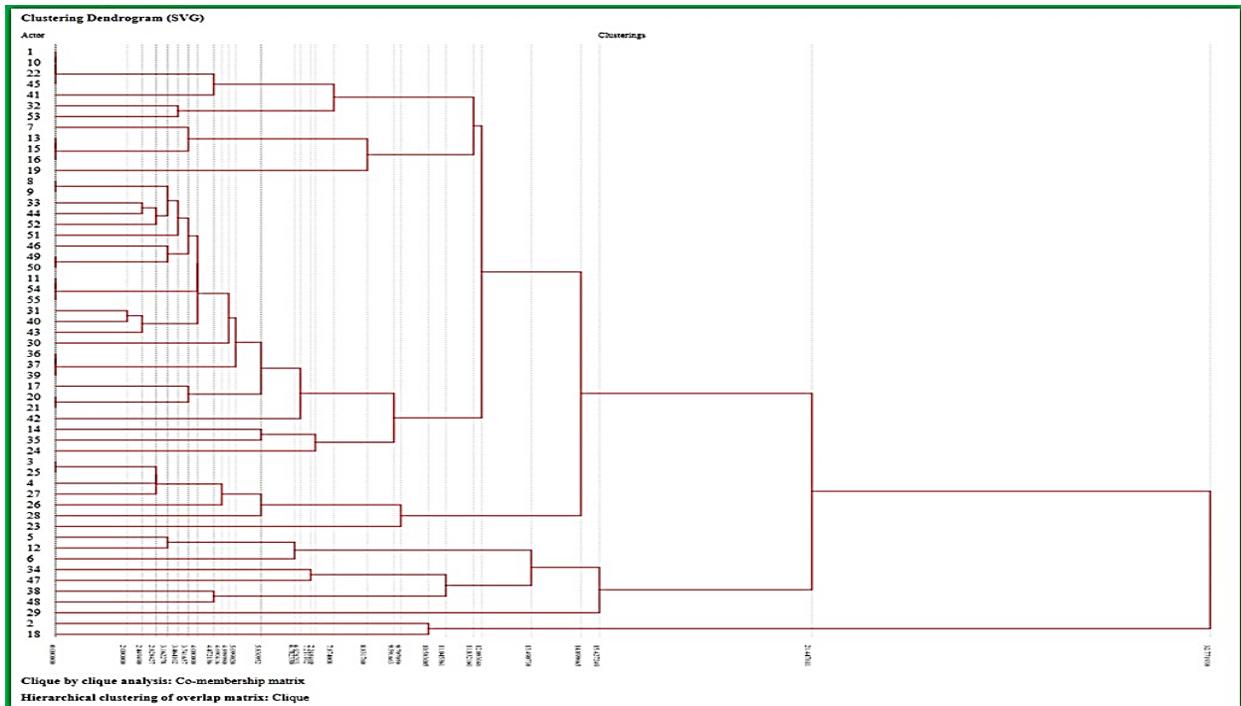


Figure 20. Subgroup Structures: Clustering Dendrogram in the Belcher-centric Network.

### Degree Centrality

Degree centrality measures how central each node is in terms of number of ties to all other nodes. The top five nodes for degree centrality are listed below, with their measures.

Table 1. Top Network Nodes for Degree Centrality

Node	Label	DC	DC'	%DC'	RANK
2	Angela M Belcher	126	0.091	9.052	1/55
18	Seung-Wuk Lee	90	0.065	6.466	2/55
34	Ki Tae Nam	79	0.057	5.675	3/55
12	Christine E Flynn	68	0.049	4.885	4/55
6	Chuanbin Mao	54	0.039	3.879	5/55
24	Forrest Liao	33	0.024	2.371	14/55
4	Nathan Ball	23	0.017	1.652	21/55

**Legend:** For this weighted Network, DC score is the sum of ties of outbound edges from each node to all its adjacent nodes: DC range:  $1 \leq DC \leq 126$ ; inverse range:  $0 \leq DC' \leq 1$ .

Degree centrality measures highlight the researchers who bridged Professor Belcher's move from the University of Texas-Austin to MIT. As PhD candidate, Seung-Wuk Lee worked with post-doctoral fellow Chuanbin Mao and Christine Flynn on using viruses to grow functional nanomaterials including quantum dots. As Professor Belcher moved to MIT, Christine Flynn transitioned the technology-focused research as a post-doctoral fellow setting up the Belcher lab at MIT, and later to Cambrios, the business Professor Belcher started with her own graduate advisor, Evelyn Hu. This work overlapped with MIT PhD candidate Ki Tae Nam's extension of the virus research to energy, creating novel nano-structured batteries. Internationality added to the diversity of the research team: Ki Tae Nam and Seung-Wuk Lee studied chemistry in Korea, and Chuanbin Mao earned his PhD in China before researching nano-biomaterials in the USA.

**PageRank Prestige**

PageRank Prestige (PRP) measures the importance of network actors linked to actors linked to the focus actor. Fundamentally, this prominence measure assesses the

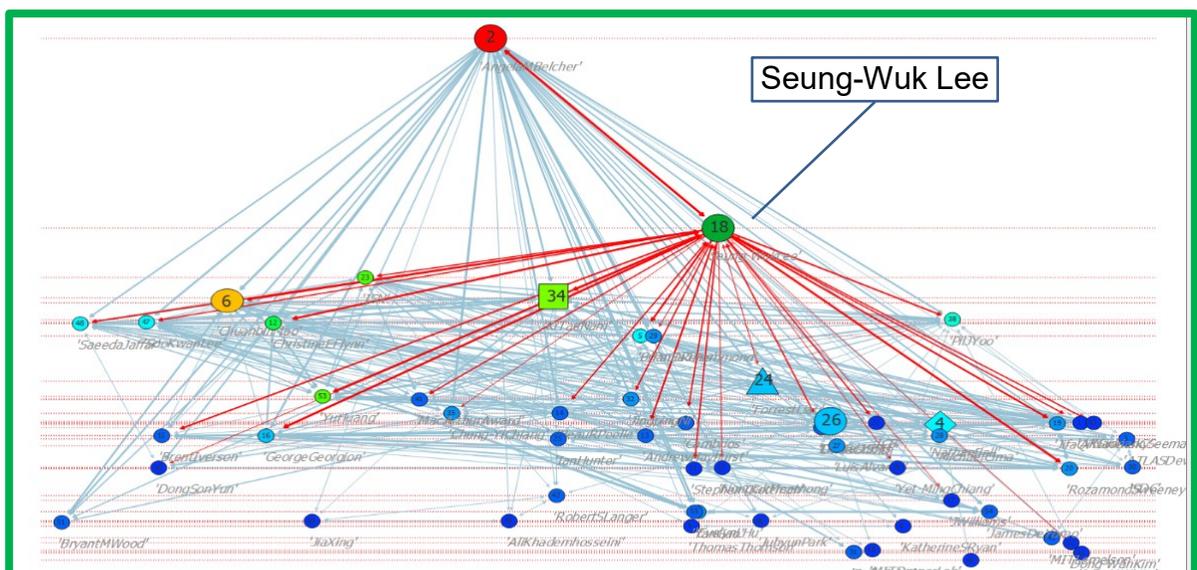


Figure 21. PageRank Prestige graph, highlighting links of Seung-Wuk Lee (Node 18).

group prestige of each actor's extended network, and theoretically the ability of the focus actor to leverage those extended links as resources. This measure leveraged the Page Rank algorithm used by Google to index web sites, based on the significance of reciprocal references from websites, co-citations, or votes linked to the node of interest.<sup>108</sup> Instead of using the metric on web site connections, I used the metric to assess co-occurrence of entities in this network. In effect, this metric shows which nodes are linked to other important nodes (having important friends with resources). For this ISN network analysis, instead of web site linkages, the comparison is made with network actors' interactional linkages based on co-authorship and co-occurrence in ISN-related entrepreneurial activities. This network's co-references are the actor co-occurrences in their research publications, Soldier Design Competition participation, UARC membership, and start-up business partnerships.

The PRP layered graph highlights the network linked with Seung-Wuk Lee (node 18) in red. This mathematical diagram shows the prominence of this node over Ki Tae Nam (node 34), and Chuanbin Mao (node 6). Further details can be assessed by the statistical measures, below, which shows the dominance of Seung-Wuk Lee, whose work was acknowledged carrying through the research from Texas to Massachusetts. The closeness of the two counterparts suggests they played similar structural roles at the two universities.

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<sup>108</sup> Larry Page et al., "The PageRank Citation Ranking: Bringing Order to the Web," November 30, 1998, <http://infolab.stanford.edu/pub/papers/google.pdf>.

Table 2. Top Network Nodes for PageRank Prestige

Node	Label	PRP	PRP'	%PRP'	RANK
2	Angela M Belcher	0.061	1	100	1/55
18	Seung-Wuk Lee	0.04	0.662	66.159	2/55
23	ISN	0.035	0.573	57.324	3/55
34	Ki Tae Nam	0.033	0.537	53.703	4/55
6	Chuanbin Mao	0.032	0.528	52.822	5/55
29	Paula T Hammond	0.029	0.469	46.876	11/55
24	Forrest Liao	0.024	0.388	38.84	12/55
26	Linda Griffith	0.019	0.317	31.672	18/55
4	Nathan Ball	0.019	0.311	31.07	24/55

**Legend:** Top five nodes for PRP are shown above, with selected other nodes. Maximum PRP is 0.061 (Angela Belcher, node 2). PRP range:  $0.004 \leq PRP \leq 0.061$ , sum = 1, and mean = 0.018. PRP' is the scaled PRP (PRP divided by max PRP).

The roles of the MIT faculty members as co-leaders of ISN research projects who also were linked with many other co-authors increased the PRP of Professors Hammond and Griffith. Graduate students involved in the Soldier Design Competition were Forrest Liao, also involved in Belcher-lab research for master's degree and PhD, and Nathan Ball. After completing his master's degree, Ball focused on commercializing his product through his start-up company ATLAS Devices, and worked closely with the ISN to do so. The ISN node reflexively shows actors' secondary connections to the ISN, since I eliminated the first-level ISN connections to focus this analysis on core relations. Secondary connections that proved important to transitioning technologies, and teaching other ISN teams to transition, were the recurring prototype demonstrations by Liao and Ball as successful entrepreneurs and technology transitioners to Soldier Design Competition audiences. (These student entrepreneurs are discussed in chapter 6.)

## Influence Range Closeness Centrality

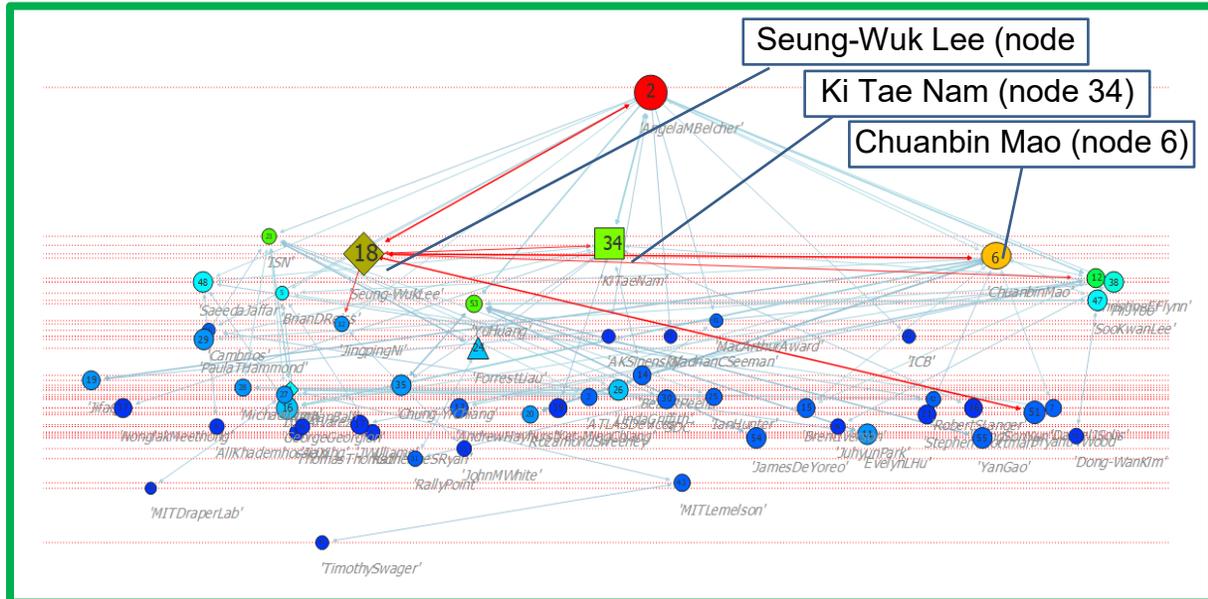


Figure 22. Influence Range Closeness Centrality in the Belcher-centric network.

The Influence Range Closeness Centrality (IRCC) counts outbound distances from each actor node to other reachable nodes, as a ratio of the fraction of reachable nodes to the average distance to those nodes, computed for every node.<sup>109</sup> Thus this measure enables an analyst to assess the reach or influence of each actor.

Table 3. Top Network Nodes for Influence Range Closeness Centrality

Node	Label	IRCC	RANK
2	Angela M Belcher	1.893	1/55
18	Seung-Wuk Lee	1.776	2/55
34	Ki Tae Nam	1.734	3/55
6	Chuanbin Mao	1.654	4/55
24	Forrest Liau	1.502	9/55
4	Nathan Ball	1.183	26/55

**Legend:** For this network, the top four nodes in terms of IRCC index are shown, along with selected others. IRCC range:  $0.547 \leq IRCC \leq 1.893$ ; IRCC mean = 1.168.

<sup>109</sup> Stanley Wasserman and Katherine Faust, *Social Network Analysis: Methods and Applications* (Cambridge: Cambridge University Press, 1994), 201, <https://doi.org/10.1017/CBO9780511815478>.

As expected, Professor Belcher most strongly influences this network. This measure enables the analyst to see how closely the next three members fall, with Seung-Wuk Lee followed closely by Ki Tae Nam and Chuanbin Mao. Clearly all three are influential members of the network, linking with many important research partners. The two masters level students are more clearly differentiated by this measure, with Forrest Liau ranked at 9 of 55 actors, while Nathan Ball is ranked close to the mean, at 26 of 55 actors. As a graduate student in the Belcher Lab, Forrest Liau links with more MIT academic actors than Nathan Ball, who links more with external actors through his start-up company, ATLAS Devices.

### **Understanding the Dynamics of this Network**

These quantitative measures from Social Network Analysis illuminate some of the inner workings of this strongly connected, fairly balanced network. Even in its early days, the key performers can be discerned by the centrality measures focused on node degree centrality, PageRank Prestige, and Influence Range Closeness centrality. Key players in the network at the faculty level are Professors Belcher, Hammond, and Griffith. The top post-master's contributors to this publication-generating research and information flow at MIT was Ki Tae Nam. Christine Flynn moved from Texas to MIT with Professor Belcher, and transitioned the technology to Cambrios. All built on foundational research done in Texas by Seung-Wuk Lee and Chuanbin Mao. The two master's students who contributed most to the dynamics of this network were Forrest Liau, followed by Nathan Ball. Without these quantitative analytic techniques, these nuanced differences in contribution to research would have been challenging to identify. Without the qualitative analysis, these differences would have been difficult to understand.

## Analysis

This case study shows the benefits of qualitative analysis in following the actors who enroll each other in basic research networks. The expected modes of enrollment of a researcher reaching out to another in the same discipline were observed. Surprisingly, the new modes of 'learn-act-assess' used by Professor Belcher to build her own interdisciplinary skills were extended from the very local mode to the establishment of a new academic department of bioengineering at MIT, adding credibility to the new academic discipline. This establishment of new disciplinary partnering demonstrated translation of this approach which required participants to cross conventional disciplinary boundaries in order to collaboratively co-create new knowledge. The patent map as an image showed how other researchers around the world acknowledged their own work as deriving from the work done by Professor Belcher and her close colleagues, demonstrating that the Belcher-focused work served as an obligatory point of passage that needed to be recognized by other researchers to have credibility in their own technology patents.

The quantitative analysis filled gaps in understanding from the scarcity of the written documents available to show how micro-actions within the research teams supported enrollment and translation. Without first-person thick descriptions of how the various members of the research teams organized their networks and collaborated, the quantitative analytics revealed the different people who had the strongest impacts on the very early stage basic research projects. Even in the entrepreneurial startup phase, these analytics enable subtle distinctions to be identified. The centrality at MIT of PhD student Ki Tae Nam was revealed through several metrics. A surprising outcome was the

structural equivalencies of University of Texas-Austin post-master's researchers Seung-Wuk Lee and Chuanbin Mao. The technology transition and bridging role was played by Christine Flynn, who moved with Professor Belcher from University of Austin-Texas to MIT, and then to start-up firm Cambrios. Future research could assess work she did to expand the ISN's portfolio of transfer-ready technologies. Finally, the recursive learning by Soldier Design Competition participants Forrest Liau and Nathan Ball demonstrated an inversion of traditional power dynamics, where entrepreneurial faculty learned from entrepreneurial students, who in turn became enrolled as participants in the ISN basic research network. This bi-directional enrollment will be explored in the next two chapters, focused on the Applied Research led by Professor Paula Hammond, and the Prototype Research case study, where Soldier Design Competition prototypes influenced the computational simulation research portfolio led by Professor Raúl Radovitzky.

## Conclusions

The qualitative methods describing detailed interactions between the network's actors and the quantitative social network analytics provided insights into how this biotechnology-focused network was connected. Although no techniques can overcome the distance in time and imperfect information, these analytic approaches combine effectively to help identify strong contributors to Professor Belcher's research networks. Significant translation and enrollment were required to create and sustain these networks. Dynamic by nature as students graduating with degrees, the networks continually need refreshment of people, research focus areas, and funding sources. Professor Belcher serves as exemplar of MIT faculty, able to initiate ISN and ICB research networks able to translate shared discoveries over distance and across many domains.

## Chapter 5.

### 6.2: Applied Research, Enrollment and Translation Networks

#### Overview

In the last chapter I analyzed actor-networks doing basic science on bio-nanotechnologies to help soldiers, emergency responders, and other users. In this chapter, I follow one actor, MIT Professor Paula Hammond, through actor-networks as she translates science to applications, enrolling allies and partners locally, across MIT, and in other US universities. As a recognized research leader who also is a minority woman, Professor Hammond spoke publicly on many occasions about her work and life. She used her personal life experiences to teach broadly, beyond academia. In addition to invited technical talks, including the World Economic Forum, her interviews were freely shared using then-emerging Internet communications such as YouTube. Key interviews where Professor Hammond gave her perspectives include a 2015 TED talk on New York's Broadway describing her cancer research, viewed by more than 1.5 million people and shown on Boston public television.<sup>110</sup> In a 2011 MIT Infinite History interview recognizing MIT's 150<sup>th</sup> anniversary, she described her scientific research and discussed issues of culture and diversity.<sup>111</sup> After leading MIT's 2007-2010 study on faculty race and diversity, she gave interviews; the University of California – Santa Barbara (UCSB) Graduate Students for Diversity in Science posted their interviews with her on YouTube.<sup>112</sup>

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<sup>110</sup> Paula Hammond, *TED Talk: A New Superweapon in the Fight against Cancer*, TED Talks Live: Six Nights of Talks on Broadway (The Town Hall Theater, New York, NY, 2015), [https://www.ted.com/talks/paula\\_hammond\\_a\\_new\\_superweapon\\_in\\_the\\_fight\\_against\\_cancer/](https://www.ted.com/talks/paula_hammond_a_new_superweapon_in_the_fight_against_cancer/).

<sup>111</sup> Chris Boebel, *MIT Infinite History Interview with Paula Hammond, MIT '84, PhD '93*, 2011, <https://infinitehistory.mit.edu/video/paula-t-hammond-84-phd-93>.

<sup>112</sup> Paula Hammond, Graduate Students for Diversity in Science Interview: The Importance of Diversity in Higher Education, May 14, 2010, [https://www.youtube.com/watch?v=zX7t\\_GsYlao](https://www.youtube.com/watch?v=zX7t_GsYlao).

In voicing professional and personal concerns, she makes tacit knowledge explicit. By following her through her networks, we see what Latour described as the “ecology of tributaries, allies, accomplices, and helpers... (by which) a substance is transformed ... from a matter of fact to a matter of concerns.”<sup>113</sup> These shared concerns shaped Professor Hammond’s research, enabling her and her team to ‘act at a distance,’ and transform institutions including the ISN and broader MIT, and STEM communities in universities across the United States.

Professor Hammond built networks that linked with fellow researchers, peers and students, who shaped her and were shaped by her work and identity. In her professional research as a chemical engineer, she designed new materials using polymer science, which transformed by changing color or structure when heated or stretched. Over her career, she translated nanoscience to engineering, creating applications for biomedicine, energy production, and cancer research. As a co-founder of the ISN, she enrolled interdisciplinary teams of participants to produce tangible capabilities at macro-, micro-, and nanoscales, while also building networks. In her personal identities as a woman and person of color, Professor Hammond also navigated the controversies and challenges of being a minority within a minority, frequently the ‘first-of-type’ in roles she undertook. She worked to increase diversity of opportunities for students, faculty, and working researchers. In her broadest reach, she worked to address controversies in race and diversity which affected students and faculty at MIT and at universities across the US, including HBCUs supported by Defense funding.

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<sup>113</sup> Bruno Latour, “Network Theory | Networks, Societies, Spheres: Reflections of an Actor-Network Theorist,” *International Journal of Communication* 5 (2011): 4.

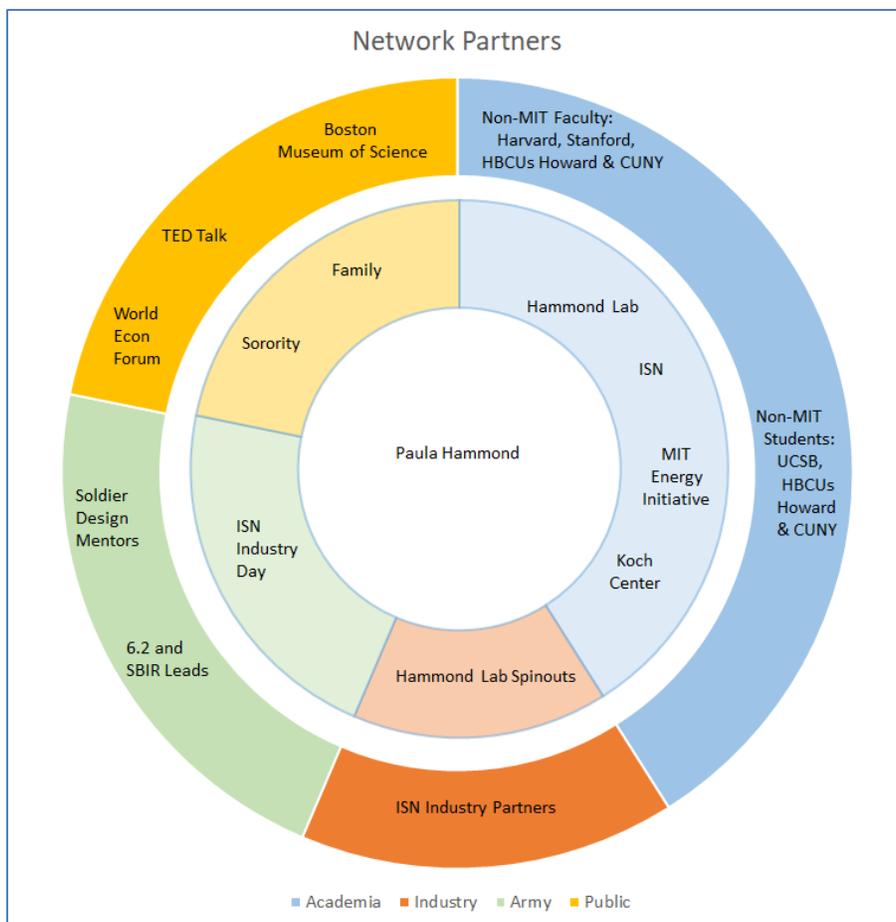


Figure 23. Professor Hammond Network Partners

## Building Credibility

To play a key role in these scientific application actor-networks at the ISN and beyond, an entry criterion is credibility as a high performing, highly regarded scientist and engineer. Professor Hammond has prolifically researched and published on many applications of polymers. She researches and designs applications to use these linked, repeating molecular chains, commonly found in applications including the polyesters used in plastic films, and biological proteins and sugars. Beginning at age 16, she moved from Detroit to study at MIT and earned her Bachelor of Science in Chemical Engineering in 1984. Rather than going directly into graduate education, she worked in industry, and

applied her expertise for two years as a process engineer for Motorola communications devices factory in Florida – the only black female engineer in a staff of two thousand people. Next, she moved to Georgia and earned her Master of Science in Chemical Engineering from the Georgia Institute of Technology. Set on an academic career, she returned to Massachusetts and earned her PhD in Chemical Engineering from MIT in 1993. Her 1994 postdoctoral assignment at Harvard University in the research group led by George Whitesides began her career of interdisciplinary research, and earned her a National Science Foundation (NSF) Postdoctoral Fellowship in Chemistry.

### **Recognized Excellence in Research**

Professor Hammond was recognized by leading organizations for excellence in scientific research. A 2015 Chemical Heritage Foundation profile highlighted her achievements and significant awards. Early honors included the NSF Career Award, Environmental Protection Agency (EPA) Early Career Award, DuPont Young Faculty Award, 3M Innovation Fund Award, and the 2010 Harvard Scientist of the Year. She continued to earn honors throughout her career:

In 2015 she was appointed head of MIT's Department of Chemical Engineering—the first woman and the first person of color to hold that post.... She has published over 250 scientific papers and holds over 20 patents....<sup>114</sup>

In 2013, Professor Hammond was one of three African-American women fellows elected to the American Academy of Arts and Sciences, an organization founded in 1780

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<sup>114</sup> Chemical Heritage Foundation, "Women in Chemistry: Paula Hammond."

to recognize excellence and serve the public good by “conven(ing) leaders in every field of human endeavor to examine new ideas, address issues of importance to the nation and the world...”<sup>115</sup> Professor Hammond’s inclusion recognized her transformative impact beyond academia and willingness to address issues important to American life. Other notable fellowships include the American Chemical Society Polymer Division, American Institute of Biological and Medical Engineers, and American Physical Society – demonstrating a span of expertise across diverse disciplines.

From the perspective of fellow scientists and research engineers, Professor Hammond’s undergraduate, graduate, and doctoral studies and research in chemical engineering made her an interdisciplinary addition to the Whitesides chemistry research group at Harvard University. Her pioneering research in nanotechnology equipped her to edit and evaluate other researchers’ submissions to the American Chemical Society’s professional journal *ACS Nano*. Being recognized by American societies focused on physics, biology and medicine, and chemical polymers reflects esteem in her ability to work with researchers from multiple disciplines in her boundary-spanning scientific roles. These attributes led her to be included in the Koch Institute for Integrative Cancer Research, performing research at MIT focused on cancer. There, she advanced layer-by-layer material self-assembly techniques for precision drug delivery. She designed and created nanoparticles by applying electrostatically charged layers of polymers, layering positively and negatively charged material with different attributes. The resulting nanoparticles were structured like candy-coated chocolates: the biocompatible outer shell could move freely through a person’s blood to the tumor, and then biodegrade as

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<sup>115</sup> American Academy of Arts and Sciences, “About the Academy,” 2018, <https://www.amacad.org>.

designed to release materials targeted to kill cancer cells. At the ISN, she applied this same layer-by-layer polymer assembly approach to designing nano-biomedical blood clotting devices to treat soldier wounds on the battlefield, with the goal of reducing battlefield deaths due to bleeding out.<sup>116</sup>

Even in her scientific research, Professor Hammond demonstrates Latour's concept of the network as implementing translations that transform all network participants, making it so that "action is radically redistributed."<sup>117</sup> Professor Hammond designed and guided the research, but the actual laboratory work with chemicals in beakers, nano-instruments, and various laboratory animals to test potential applications were performed by graduate students, undergraduate researchers, and post-doctoral associates. These many people brought diverse skills and experiences, as well as their own network affiliations. Yet for the sake of coherence and reputation benefit, individuals are subsumed under the group name 'The Paula T. Hammond Lab,' as they join academia, government, and industry, as profiled in the journal *Science*.<sup>118</sup>

In addition to partnering with faculty researchers across MIT, Professor Hammond's network expanded to include students who were involved in the ISN Soldier Design Competition. These undergraduate innovators became graduate student researchers performing research into applications of material science – avoiding a leak of talent where promising researchers move from academia to industry. For example,

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<sup>116</sup> Paula Hammond, "Nanodays 2012: Engineering Medical Treatments" (May 29, 2012), <https://www.youtube.com/watch?v=HgChqXALlsk>.

<sup>117</sup> Latour, "Network Theory | Networks, Societies, Spheres: Reflections of an Actor-Network Theorist," 2011.

<sup>118</sup> John Bohannon, "The Paula T. Hammond Lab," *Science*, December 3, 2014, <https://www.sciencemag.org/careers/2014/12/paula-t-hammond-lab>.

from the ISN Soldier Design Competition team RallyPoint, who designed a glove that translated soldier hand gestures to computer input signals, two team members became graduate researchers who earned MIT PhDs. Forrest Liao worked on a project led jointly by Professors Hammond, Angela Belcher, and Yet-Ming Chiang to design batteries using M13 viruses to self-assemble nanowires with electrical components.<sup>119</sup> The same combination of self-assembly with viruses and layer-by-layer applications was used to increase the efficacy of solar cells for portable energy. As Professor Hammond briefed President Obama during his 2009 visit to MIT, increasing energy efficiency promised benefits both for people in America and around the world.

Forrest Liao's RallyPoint teammate Bryan Hsu worked with Professor Hammond for both masters and PhD degrees. His projects applied the layer-by-layer polymer design to nano-biomedical applications. One application was a bandage for soldier or emergency use, which tailored layer-by-layer stacks of blood clotting, pain relief, and antibiotic agents to stop wound bleeding. Materials designers could vary the stacked material combinations, and time-release sequence of different components. Applications for this tailored drug delivery technology included needle-less vaccinations which include the vaccine booster, reducing follow-up visits to get shots at a doctor's office. Another application pretreated biomedical implants such as hip replacements, reducing the time and number of surgeries needed to replace a hip by integrating antibiotics to fight infection. A third layer-by-layer application treated glaucoma with an easily used contact

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<sup>119</sup> K. T. Nam et al., "Stamped Microbattery Electrodes Based on Self-Assembled M13 Viruses," *Proceedings of the National Academy of Sciences of the United States of America*, 2008, <https://doi.org/10.1073/pnas.0711620105>.

lens coated with medicine. While creating technologies focused on transition, each project enabled researchers to produce multiple articles published in peer-reviewed journals.<sup>120</sup>

In addition to working with talented student researchers, these research collaborations enabled the MIT professors to create new partnerships. Professor Hammond also gave first-person accounts of collaboration creation, making tacit knowledge explicit with a 'how-to' description of teaming with fellow researchers. In her MIT Infinite History interview, Professor Hammond described how the ISN brought her collaboration with Professors Belcher and Yet-Ming Chiang, creating a multi-disciplinary team that could translate knowledge and technologies:

We came together ... through the ISN. Angie was just coming on board at MIT.... We really clicked... By combining water-based electrostatics with viruses which have an inherent charge, ... we could actually incorporate the virus in a unique way in these layer by layer films to get ordered structures... a virus battery. And we brought Yet-Ming Chiang in....<sup>121</sup>

### **Technologies in the World**

Gaining scientific knowledge for its own sake offered benefits, increasing both the researcher's personal knowledge and extending humanity's awareness. However, the MIT motto 'Mens et Manus,' which translates from Latin to 'Mind and Hand,' emphasizes the value of practical applications of educational learning. As a way to bring technologies

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<sup>120</sup> Bryan B. Hsu et al., "Multilayer Films Assembled from Naturally-Derived Materials for Controlled Protein Release," *Biomacromolecules* 15, no. 6 (June 9, 2014): 2049–57, <https://doi.org/10.1021/bm5001839>; Bryan B. Hsu et al., "Ordered and Kinetically Discrete Sequential Protein Release from Biodegradable Thin Films," *Angewandte Chemie International Edition* 53, no. 31 (July 28, 2014): 8093–98, <https://doi.org/10.1002/anie.201403702>.

<sup>121</sup> Boebel, *MIT Infinite History Interview with Paula Hammond, MIT '84, PhD '93*, 2011.

into the world, entrepreneurship was valued at MIT. In 1997, two years after Professor Hammond joined the MIT faculty, BankBoston published the first study of the impact of entrepreneurial firms from MIT. The 'Founders Report' surveyed MIT alumni founders, who as a group established businesses at an average rate of 150 per year, and assessed the economic impact of new enterprises emerging from MIT.

If the companies founded by MIT graduates and faculty formed an independent nation, the revenues produced by the companies would make that nation the 24th largest economy in the world. The 4,000 MIT-related companies employ 1.1 million people and have annual world sales of \$232 billion ... less than the GDP of South Africa and more than the GDP of Thailand.<sup>122</sup>

The report captured beliefs of MIT alumni that successfully completing an MIT education brings self-confidence and reinforces the value of bright people collaborating to solve problems together. The government role is seen as supportive, investing in research, including funding tuition and stipends to support graduate students performing research such as done at the ISN.

The startup businesses established around the ISN and MIT research provided another set of interlocking networks bringing together Professor Hammond and other ISN participants. In addition to transitioning technologies to ISN industry partner firms, the ISN structure encouraged creating entrepreneurial companies. The student companies established for the Soldier Design Competition, such as RallyPoint, demonstrated the

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<sup>122</sup> Ed Moscovitch et al., "MIT: The Impact of Innovation" (Cambridge, MA: BankBoston, March 1997), [http://www.saveourheritage.com/Library\\_Docs/Bank%20Boston%20Impact%20of%20Innovation.pdf](http://www.saveourheritage.com/Library_Docs/Bank%20Boston%20Impact%20of%20Innovation.pdf), p. 4.

benefits and pitfalls of this mode of networking. Faculty also engaged in these entrepreneurial activities. While working with established firms, Professor Hammond also established companies with and by her students and research partners to commercialize her patented technologies. These firms included Svaya Technologies, using layer-by-layer techniques for electronic displays, and LayerBio, applying layer-by-layer nanomedicines to glaucoma and wound care.

## **Building Institutions**

As a co-founder of the ISN, Professor Hammond provided a unique insight into how MIT approached the ISN contract competition. Normally, proposals for these competitive actions are closely held within each of the competing institutions, the academic equivalent to proprietary advantage in bidding for a business contract. Professor Hammond's description of the ISN proposal process is noteworthy, since discussion on the lead-up to the ISN competition is scarce. Perhaps due to the controversy resulting from the MIT team using intellectual property of the Lai Brothers in the Radix comic heroine as the basis for the proposal cover art, the MIT ISN proposal itself does not appear to be publicly discoverable; neither MIT nor the military have made copies available as originally described during the ISN Request for Proposal process. However, as part of her efforts to make tacit knowledge explicit to help other faculty and students build collaborations, Professor Hammond described aspects of the competitive process, offering the ISN collaboration as an example for building further collaborations.

## **Competing for the ISN**

In her MIT Infinite History interview, Professor Hammond described the network that built MIT's 2001 proposal to the competition to host the ISN as a strategic, long-term

Department of Defense University Affiliated Research Center (UARC). As a junior faculty member, she saw the ARO announcement for the competition and began discussing within her network. The proposal team built like a snowball. She and chemistry professor Timothy Swager were collaborating on a different Army grant to create electronic displays. Both agreed in the merit of competing, and approached Professor Ned Thomas, who had served on Professor Hammond's thesis committee. Professor Thomas brought in Dr. Bill Peters, later the ISN's Executive Director, and all four developed an outline for the proposal to create a center using nanotechnologies to improve soldier protection. She described the process of enrolling fellow members across different departments at MIT:

We wrote the proposal together. We solicited from the MIT community.... a bottom up operation... People showed interest... wrote subsections of proposals... proposed new ideas based on their technologies. We put that proposal in at the end of 2001. By that time ... unfortunately 9/11 had happened. And the sense of urgency around the need to develop these kinds of technologies increased. We were funded in 2002....<sup>123</sup>

The proposal development and submission process enrolled large numbers of MIT faculty, who committed to do research which was required to be interdisciplinary, involving two or more departments. This interdisciplinary approach shaped student research, where faculty from two or more departments oversaw graduate student research. Project proposals involved faculty from multiple departments and academic areas. Publications were inter-disciplinary. Applied research projects required participation with members of

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<sup>123</sup> Boebel, *MIT Infinite History Interview with Paula Hammond, MIT '84, PhD '93*, 2011.

the Army S&T community, and could include Army officers completing graduate studies. Outreach included a variety of Army users.

The build-out of the networks beyond MIT continued with the first ISN Industry Day, held on 25 November 2002. The ISN Director reported, “More than 110 people attended, representing companies large and small, universities, U.S. Army laboratories, National Laboratories, the media, and MIT.”<sup>124</sup> Participants were invited to review the Summary of Consortium Membership, as they listened to orientation briefings from Army sponsor and ISN leadership team. Not coincidentally, reflective of participants’ expertise and concerns, presentations showed balance and diversity in gender, roles, departments, and research focus areas. Vice President for Research Alice Gast opened by reaffirming MIT’s commitment to the ISN, followed by ARO sponsor representative Dr. William Mullins describing Army expectations of industry partners. ISN Director Thomas and Associate Director Professor Swager described research objectives focused on human performance enhancement. Professors Hammond and Linda Griffith outlined research focused on improving human protection and injury treatment. The MIT Intellectual Property Counsel, Ms. Ann Hammersla, J.D., detailed how intellectual property rights would be established with ISN industry partners, a critical enabler for manufacturing and marketing. Industry Day closed with Professor Swager describing the process of becoming an ISN industry partner and networking. Audience members could see opportunities to align themselves and their research interests with different ISN leaders who spoke. The ISN network had extended to other networks.

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<sup>124</sup> Edwin L. Thomas, “First ISN Industry Day,” November 25, 2002, <http://web.mit.edu/isn/industryday/index.html>.

## Building Out Networks

Professor Hammond built out her research partnerships with her fellow ISN researcher, Professor Angela Belcher. For the MIT Energy Initiative, both partnered with an Italian energy company to apply their material self-assembly approaches to design materials for more efficient solar energy. Professor Hammond describes the excitement of this collaboration: “It’s one of the real joys in my research lab to be able to both work with Angie and to work on this particular problem....”<sup>125</sup> Both research leaders then went to work together at the Koch Institute for Integrative Cancer Research, which explicitly focuses on interdisciplinary teaming to research cancer treatments. The cross-network enrollment continued there, as Professor Hammond described new ways to learn about other’s ideas and work, such as sharing a building and meeting together for researcher retreats. Similar to the way the ISN community came together in a 2-floor facility linked by open stairs, sharing a facility and having casual routine interactions built the Koch community and created opportunities to work together to solve challenging problems. Professor Hammond described the importance of working with people from many disciplines. She set forth a vision of a new mode of collaboration, working in deep collaboration with fellow researchers, experts in physics, biology, and medicine:

[M]ore than just having a collaboration in which one person does part A of the project, and the other person does part B of the project, and you write a paper with A and B divided. More and more we're finding these collaborations where we talk about and share our ideas... we begin to

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<sup>125</sup> Boebel, *MIT Infinite History Interview with Paula Hammond, MIT '84, PhD '93*, 2011.

generate new things, new materials, new products, new approaches that wouldn't exist if we were isolated....<sup>126</sup>

Collaboration can be increased by working together, not in parallel. Dialogue is fruitful. This cross-disciplinary, 'many views' approach to science extends to including users, as well as non-participants, under-represented minority faculty and students in collaborative endeavors. Professor Hammond extended this new approach to collaboration beyond the ISN's walls.

## Listening to Users

STS scholars study users and non-users, seeking to understand how users co-construct new technologies with designers, how technologies shape their users, and how users innovate from original uses to invent new applications.<sup>127</sup> The reasons non-users do not consume specific technologies or participate in development can also inform potential design of technologies or even technology service offerings. The ISN was established by the Army to increase the involvement of user subject matter experts – soldiers who would carry and use proposed technologies – inside the invention and innovation process, not as post-design consumers, but as co-producers. For Professor Hammond, considering 'non-users' included looking at how to increase the participation of under-represented minority among faculty and students, to grow the involvement of people from many groups in solving important problems together.

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<sup>126</sup> Boebel.

<sup>127</sup> Oudshoorn and Pinch, *How Users Matter*.

## Enrolling Army Scientists and Soldiers

As Professor Hammond related to a public audience at the Boston Museum of Science Nano Days 2012, one ISN focus area was to create nanotechnologies to save the lives and limbs of soldiers injured on the battlefield. At that time, battles waged in both Iraq and Afghanistan created awareness and a sense of urgency to motivate wound treatment and healing. She leveraged her partnerships to have discussions and learn from Army medical researchers. Professor Hammond described how a recently deployed solution, a powder to quickly clot soldiers' wounds, did work, but often caused second-degree burns in the wound. The cure brought unwanted and difficult to cure secondary problems. In response to this challenge and imperfect solution, Professor Hammond described her recent design and creation of "a spray coating that helps blood clot almost instantly, a technology that could save thousands of lives and limbs on the battlefield every year."<sup>128</sup> She had further discussions with Army medical researchers and with recent combat veterans, including Army officers attending MIT for graduate school. As a result, she refined the spray application of this rapid blood clotting solution. Her research team developed an easy-to-use, shelf-stable, portable sponge coated with thrombin blood-clotting enzyme, which could be applied in urgent circumstances to stop bleeding within a minute. By having ongoing discussions with Army scientists, officers, and leaders who visited the ISN, faculty were able to understand core issues of concern to targeted users. The experiences of soldiers working in all geographic regions, in all terrains, under all weather conditions, provided several challenges to basic survival and operations, on battlefields and beyond. The same challenges could face people recovering from natural

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<sup>128</sup> Chemical Heritage Foundation, "Women in Chemistry: Paula Hammond."

disaster, often helped by soldiers and service members, as well as outdoor enthusiasts. Awareness of the challenges, in context, presented MIT researchers with opportunities to solve interesting and compelling problems.

Professor Hammond's understanding of this particular problem was further informed by her graduate student, Bryan Hsu, whose Soldier Design Competition team RallyPoint had networked with Army soldiers to design digital gloves for computer input. (The RallyPoint example will be discussed in more detail in the next chapter.) In March 2004, the student team traveled to the Joint Readiness Training Center (JRTC) in Louisiana to observe the Opposing Force soldiers from 1<sup>st</sup> Battalion, 509<sup>th</sup> Infantry Brigade (Airborne). By listening to these users of current soldier gear, the MIT team could learn about operational constraints. By describing their proposals to translate soldiers' hand gestures and signals into digital input for soldier-carried computers, the researchers and soldiers could collaborate on defining the problem in a realistic manner and vet potential solutions. In turn, this bi-directional enrollment of researchers and soldiers enabled RallyPoint to successfully compete for and win a Small Business Innovation Research (SBIR) grant sponsored by the Army Natick Soldier Center. In addition to enrolling soldiers and student researchers, Professor Hammond demonstrated how MIT faculty listened to students to learn from their experiences, in some senses inverting traditional power relationships. This process demonstrated respect for the students, emboldening them as researchers, entrepreneurs, and collaborative partners.

### **Enrolling Cancer Patients**

The productive collaborations between Professor Hammond and Defense-funded researchers extended, when she received the Teal Innovator Award. Familiarity with

Hammond and her work created sponsorship and advocacy within the Army S&T community. This 5-year program, funded by the Department of Defense Ovarian Cancer Research Program, provided \$3.7 million in support to research specific cancers. Professor Hammond partnered with Michael Birrer at Massachusetts General Hospital, which was an industry partner of the ISN. They built out the collaboration with Ronny Drapkin at Harvard's Dana Farber Cancer Institute. Professor Hammond described the impact lung cancer had on her family as motivation.<sup>129</sup> Fighting ovarian cancer provided a compelling target, given the relative lack of progress in decades and the challenge of drug-resistant cancer recurring after chemotherapy. Combination therapies delivered RNA agents to block a specific cancer gene along with an anti-cancer drug. Professor Hammond integrated outreach initiatives, listening to cancer survivors and their families at Koch Center symposia. Cancer patients enrolled themselves and their families to provide researchers feedback and participate in therapeutic trials. Her TED Talk on fighting cancer with these layered nanoparticles was seen by more than a million people, increasing public awareness and attracting even more research collaborations.

### **Enrolling the Many to Increase the Few**

As an African-American woman, Professor Hammond's personal story highlighted challenges faced by minority scientists and engineers. In interviews, she openly described growing up in Detroit in the Civil Rights era. After attending an all-black elementary school, she and her family moved as the first black family in a white neighborhood so she could attend a racially integrated Catholic high school. Her father was a PhD biochemist and

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<sup>129</sup> Denis Paiste, "Faculty Highlight: Paula Hammond," *MIT News*, June 18, 2014, <http://news.mit.edu/2014/faculty-highlight-paula-hammond>.

mother had a master's degree in nursing. Both worked in health positions, and her mother was Dean at a community college nursing program that started after the Detroit riots highlighted the need for community-based health services. Both parents expected her to go to college and do well.

Entering MIT, Professor Hammond experienced normal confidence challenges. All MIT students performed well in high school, often without competition or peers. Entering a population of smart, high-performing students can be unsettling for everyone. For the minority students, however, racial bias was generalized to the group, with letters in the campus paper against affirmative action programs to encourage more minorities in higher education. As one of 45 black students out of 1000 in her freshman class, and one of only 15 black women, she was a 'minority of a minority.' She was often the only African-American student in recitations, and had only one black teaching assistant as an undergraduate. Subtle biases were shown in attitudes of fellow students who chose her last as lab partner and treated her as less capable than others:

Students... had attitudes and would give off the air of ...'I know why you're here' as opposed to 'How did you do on that exam' or 'Let's exchange information.' It was not common for me to be approached ... 'What did you think of that last p-set?'<sup>130</sup>

Other classmates would be sought as sources of expertise and help on homework problem sets (p-set), but were surprised at how well she did academically.

In her post-graduation work as a process engineer at Motorola, the biases and harassing actions were more overt. Supervisors told jokes about women engineers during

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<sup>130</sup> Chemical Heritage Foundation, "Women in Chemistry: Paula Hammond."

the 18 months that she was the only women engineer. Desirable work assignments would be given to the men, and she would receive less relevant tasks. Performance ratings would naturally favor the engineers who performed the more relevant work. Less subtle attitudes were demonstrated when peers disrupted her presentation by dis-arranging her slides and giggling at her discomfort.

Racially charged comments were designed to cause discomfort and alienation. Professor Hammond notes that work environments became more favorable to women, but her candid comments are striking when such issues are rarely discussed openly. By sharing her personal travails on the way to success as a researcher and MIT leader, she offers perspective and solace.

### **Increasing Diversity of MIT Faculty and Students**

Given her own experiences, and the continued scarcity of minority STEM faculty and students, Professor Hammond has led efforts to increase diversity locally on MIT and nation-wide. In her research collaborations including the ISN, MIT Energy Initiative, and the Koch Institute, faculty of both genders play key leadership roles. Students come from a diverse range of backgrounds and groups. In 2007, after a faculty member was denied tenure and alleged racial bias, Professor Hammond led the study on faculty diversity and race. Unlike the MIT studies on women in science and engineering in the 1990s, which led to success in recruiting and retaining women faculty and students, minorities continue to represent less than 7% of the MIT faculty. While the study identified this issue as common with peer institutions at Harvard and Stanford, the goal was not to be better than the others. Professor Hammond called for a revolutionary change in faculty perspectives,

moving beyond recriminations, to actively change how under-represented minorities are recruited and retained:

...Think about what we can gain.... When we began to realize that this is ... a huge plus, then we're all in... walking around at conferences and seeing potential talent, ... so we can begin to transform the world of science so that it looks like the rest of the world...<sup>131</sup>

She argued that in addition to recruiting minority faculty, the pipeline of STEM graduate students needed to be increased. MIT was hiring from only a handful of schools, competing with Harvard and Stanford for only a small number of minority researchers. Broadening the pipeline included looking more deeply at other schools for excellent students, and working to retain the researchers brought on board.

Obstacles to retaining minority faculty included their lack of basic knowledge of what actions are building blocks to support tenure. Different departments value the first successful proposal to the National Science Foundation or the National Institutes of Health differently. Junior faculty need mentoring to identify what conferences will help gain exposure, so that peers can write them letters of support for tenure. Presenting research too soon or without solid results can damage credibility, so timing the exposure is essential. Instead of isolating minority faculty for mentoring, the report recommended that all junior faculty be mentored to understand key processes and how to build a successful academic career.<sup>132</sup>

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<sup>131</sup> Boebel, *MIT Infinite History Interview with Paula Hammond, MIT '84, PhD '93*, 2011.

<sup>132</sup> Paula Hammond and Lotte Baily, "Report on the Initiative for Faculty Race and Diversity" (Cambridge, MA: Massachusetts Institute of Technology, 2010), [http://facultygovernance.mit.edu/sites/default/files/reports/2010-02\\_Initiative\\_for\\_Faculty\\_Race\\_and\\_Diversity.pdf](http://facultygovernance.mit.edu/sites/default/files/reports/2010-02_Initiative_for_Faculty_Race_and_Diversity.pdf).

Another perceived obstacle is the impact of an academic career on family life. Here again Professor Hammond gives examples of balancing work and her own life. She described her career sequence in Alumni of MIT Association (AMITA) oral history. After marrying and working in industry for two years, earning her master of science from Georgia Tech, she came back to MIT for her PhD. In her third year of graduate school, she had a baby, while living in MIT graduate housing. After her PhD, she did postdoctoral research at Harvard and returned to MIT as junior faculty. During that time, she divorced her first husband, raised her child as a single parent, remarried in 2000 while proposing for the ISN, and received tenure in 2002. She described her 'fascinating family,' including the transformation of her child:

...married to my husband, John Hammond and I had a daughter. And my daughter is now my son. He's transgender. His name is James, and he's 20 years old.... And he is just infinitely interesting in terms of everything that he does.<sup>133</sup>

Certainly, family life can bring complexity -- but people figure out how to balance work with their personal lives, and live enriched lives as a result of the diversity of responsibilities and family connections. Professor Hammond's attitude of inclusivity also opens avenues for students and faculty with many different backgrounds to expect to be accepted and valued as members of the community.

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<sup>133</sup> Boebel, *MIT Infinite History Interview with Paula Hammond, MIT '84, PhD '93*, 2011.

## Encouraging Diverse STEM Students at MIT and Elsewhere

In addition to mentoring faculty and students at MIT, and looking to recruit talented researchers at conferences, Professor Hammond extended her efforts to increase diversity in STEM beyond MIT. She gave outreach presentations to build awareness after the 2010 Faculty Race and Diversity report was released. Her interviews sought to increase the pipeline of under-represented minority undergraduate and graduate students, to create opportunities to grow the community. From the ISN, she also reached out to partner with students and faculty at HBCUs.

During this time period, HBCUs faced unexpected difficulties. The Defense Authorization Act of 1991 (Public Law 101-501 Section 832) had established a Department of Defense-wide program designed to build infrastructure in STEM programs. The Army Research Office administered this program, funding HBCU/Minority Institutions to “enable them to participate more fully in defense research and to recruit more students in these disciplines.”<sup>134</sup> However, legal challenges had limited access to HBCU funding. The case, the Rothe Development Corporation vs. the US DoD and the US Department of the Air Force, started in 1998. A contract award was challenged when the Air Force awarded a contract to an Asian-American-owned firm, despite the fact that the lowest bidder was Rothe, a small business owned by a Caucasian woman. Based on this constitutional challenge, monies could not be spent on some federal programs which favored contract awards to socially and economically disadvantaged groups. Legal challenges wound through the courts until the Supreme Court released its judgement in

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<sup>134</sup> US Army Research Office, “ARO In Review 2010” (Research Triangle Park, NC, January 2010), <https://apps.dtic.mil/dtic/tr/fulltext/u2/a561692.pdf>.

2017. In the meantime, HBCU funding was impacted.<sup>135</sup> Through the ISN, Professor Hammond started a research initiative to partner with two impacted HBCUs, Howard and City University of New York.<sup>136</sup> Joint research projects, site visits, and training to use ISN instruments increased capacity in this collaboration and likely increased the commitment and morale of HBCU students and faculty.

While personal outreach and research partnerships between members of the elite university and HBCUs benefited involved students and faculty, larger structural issues impacted the ability to increase diversity in the pipeline of scholars. In this period, federal research funding shifted focus from long-term sustained support programs, described in STS literature as classic Mode 1 scientific research, to a new approach, Mode 2 research. This new approach favors short-term projects focused on delivering applications.<sup>137</sup> The ISN contract showed a preference for Mode 2 research: short-term, agile, project-based research that delivers tangible applications in addition to new knowledge.

In order to build the student and faculty pipeline to increase the diversity of under-represented minorities in STEM, HBCU leaders expressed the need for long-term strategic partnerships.<sup>138</sup> This need was highlighted in a 2014 National Research Council review of Army Research Lab support for HBCUs. The study committee visited eight HBCUs, including City University of New York, Hampton University, Howard University,

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<sup>135</sup> US Army Research Office.

<sup>136</sup> John D. Joannopoulos, "MIT Reports to the President 2007–2008: Institute for Soldier Nanotechnologies" (Cambridge, MA, June 30, 2008), <http://web.mit.edu/annualreports/pres08/2008.08.10.pdf>.

<sup>137</sup> Helga Nowotny, Peter Scott, and Michael Gibbons, "Introduction: 'Mode 2' Revisited: The New Production of Knowledge," *Minerva*, Special Issue: Reflections on the New Production of Knowledge, 41, no. 3 (2003): 2, <https://doi.org/10.1023/A:1025505528250>.

<sup>138</sup> National Research Council, *Review of Army Research Laboratory Programs for Historically Black Colleges and Universities and Minority Institutions* (Washington, D.C.: National Academies Press, 2014), <https://doi.org/10.17226/18963>.

Morgan State University, Navajo Technical University, North Carolina A&T State University, Prairie View A&M University, and the University of New Mexico at Albuquerque. Non-attributed discussions with faculty identified strengths and concerns about HBCU funding from the Army. Common themes included acknowledgement of the positive impact of funding for academic programs, faculty, infrastructure, and student support. The STEM basic research performed at these HBCUs was viewed as high quality and relevant to Army goals: “Students who presented their work demonstrated confidence, knowledge, and passion for their work. The supported faculty members were aware of ... advances in their respective fields.”<sup>139</sup> Institutions leveraged Army funding to gain grants from other federal research funders.

However, concerns emerged about the short-term focus of the research support. Short-term grants for research or specific equipment did not help with institutional development. Multi-investigator grants supported collaborations, within the institution and with other universities, generally seen as beneficial. Collaborative projects with other institutions helped build institutional capacity. Advice from partner institutions helped, but multi-institution partnerships required caution, and needed careful management:

...[T]o avoid the perception ... that HBCU/MIs are sometimes regarded as second-tier participants by both other research institutions ... and ARL staff. It is necessary to treat HBCUs/MIs from the start as full partners in any collaborative enterprise....<sup>140</sup>

Professor Hammond advocated new collaboration modes to expand STEM.

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<sup>139</sup> National Research Council.

<sup>140</sup> National Research Council.

Equality in peer partnerships is as important as sustained research partnerships with the Army. These sustained research partnerships also allow for development of early-career faculty. In addition, longer research support programs allow for stronger collaboration. Sustained research grants enabled faculty to build programs that avoid discontinuities and gaps. Long-term programs can provide students funding for the duration of their graduate study – as long as seven years, compared with short 3-year research grants focused on Mode 2 research with delivery of applications. The observations and concerns of these HBCU faculty members shape the overall efforts to increase diversity in science and engineering by growing the pipeline of STEM scholars. This effort can transform innovation by freeing more people to contribute their ideas, their talent, and their hard work to solving the world's problems – at MIT and beyond.

## **Analysis**

Professor Hammond demonstrated excellence in applied research. To serve as a role model as a scientific leader and mentor, she made tacit knowledge explicit, explaining to all members of MIT and other faculties how to stage progress to become tenured faculty. Her actions performed network-building using enrollment techniques, to enable action at a distance -- geographically and far into future time. Instead of singling out under-represented minorities for public mentoring, which could suggest 'less than' capabilities among minority current and potential faculty, Professor Hammond advocated for low-key mentoring and articulated new modes of collaboration. Her outreach to HBCU scholars, starting as undergraduates, enabled a new pipeline for future faculty at elite US research universities. To participate in nanotechnology development, near-peer partnering with

scientific scholars is needed to enable translation. To transform the US community and increase STEM scholars overall, a sustained effort will be required for years.

Another complicating factor arises from the preference among research sponsors for Mode 2 agile research focused on technology transfers. Discussion among HBCU research leaders about challenges of Mode 2 rapid reconfiguration research, compared to preferences for sustained Mode 1 research, highlights sustainment and growth needs of the broad research community. The far-ranging outreach among many publics enabled Professor Hammond to transform the way scientists emerge from US schools at all levels.

## Conclusions

The many networks that Professor Hammond operates within and across demonstrate an ecology of connections as described by Latour. Following this one actor through her networks foregrounds the complexity of accomplishing this pioneering research. She extensively builds collaborations, extending alliances and partnerships to do leading-edge science and engineering. Her networks work collaboratively to improve soldier battlefield injury response, solar energy efficiency, and cancer treatment. Professor Hammond also works to improve the capacity of these networks, increasing diversity in the STEM pipeline. In working with HBCUs, Professor Hammond helped colleagues in Howard University and City University of New York participate as collaborative partners, overcoming systemic concerns. She provides herself as an example and role model, describing her challenges explicitly and making tacit knowledge available to help others envision themselves as achieving results. In the next chapter, I will describe other aspects of the networks emerging from the ISN: student teams and ISN researchers teaming to build prototypes that transform operations.

## Chapter 6.

### 6.3: ISN and the Soldier Design Competition: From Prototyping to Brain Research

#### Overview

A significant challenge confronting the ISN was the requirement to show tangible results in terms of technology transfer. However, long-term, fundamental research takes time to produce tangible results to improve human protection. To create a new technology pipeline, the founding ISN Director established the Soldier Design Competition to engage undergraduates with ISN graduate students and faculty, growing the talent pipeline and generating interest in the ISN. The Director reported the engagement and resulting successful prototypes to the MIT President in his annual reports. Defense Department participants were impressed by the speed, productivity, and creativity demonstrated by volunteer student teams. This competition created new avenues for enrollment. Army leaders and research and development partners engaged throughout the year, in defining challenges, providing mentors to student teams, judging semifinals and finals, and providing outreach and connection to Defense Small Business Innovation Research (SBIR) funds. The Soldier Design Competition showcased a range of usable prototypes that spurred other research and innovation, by teams from MIT and US Military Academy at West Point. Three cases will be examined: RallyPoint's Handwear Computer Input Device; ATLAS Powered Rope Ascender; and the Blast Dosimeter. The Blast Dosimeter project catalyzed the Army Acquisition community to procure and field thousands of helmet-mounted brain sensors to soldiers in Iraq and Afghanistan in record time. The

brain sensors catalyzed extensive brain research in traumatic brain injury, the results of explosives blasts that were identified as the 'signature injury of the current wars.'

## **Technology Transfer via Prototypes**

The ISN sought a means to 'prime the pump,' creating new pathways and building trusting relationships to transition new technologies from the lab to soldiers in the field. Both enrollment and translation were critical mechanisms to support this transition focus. The basic and applied research portfolios represented longer-term, more significant, more high-risk transitions than student team prototypes created within six months for the Soldier Design Competition. Students were engaged and encouraged to compete for prizes between \$5,000 and \$1000, provided on a non-equity-diluting basis by ISN industry partners. Student teams at MIT, and later West Point, self-organized and selected between six defined challenges to prototype a solution within six months. Teams could also propose their own challenge, defining the requirements and proposing a solution, in conjunction with military mentors. The resulting prototypes were demonstrated before a live MIT audience, with judges from academia, industry, and the Army. Teams were encouraged to consider forming start-up businesses, filing patents, and commercializing.

Defense leaders, including Secretary of the Army Francis Harvey, saw the Soldier Design Competition as providing a means to demonstrate rapid development and rapid acquisition methods. Military mentors found the Soldier Design Competition a useful venue to partner with students and faculty, building the actor-networks described by Latour.

## **Military Mentoring**

Major Rex Blair, a Harvard Applied Physics master's student and Uniformed Army Scientist at the ISN, had an office on the ISN facility 4th floor. He described his role: "...as on-site military liaison, people get immediate feedback from me as combat commander on technology uses.... The SDC works as a rapid innovation program, helping the soldier today."<sup>141</sup> Major Blair also became involved in an innovative applied research project with ISN Professor Yoel Fink, using fiber sensors for laser-based communications. He briefed the 2007 Pacific Command (PACOM) Operational Science and Technology Conference with his fellow ISN researcher and Soldier Design Competition award winner, Nathan Ball, who co-invented the ATLAS powered rope ascender. Their presentation message was that innovative people at MIT's ISN had solved current soldier challenges with practical, usable devices; and these same innovators could solve new problems rapidly and with results suitable to support military operators and emergency first responders.

## **Three Student Prototype Case Studies**

### **RallyPoint and the Handwear Computer Input Device**

At the first Soldier Design Competition started in 2003, an undergraduate team called the Surreptiles demonstrated a glove-based gesture translator, for computer input. Their military mentor was Major Blair, who taught the student team led by Forrest Liao many standard hand and arm signals used by soldiers to communicate without words. The team studied brain science studies on cognitive overload. Using emerging scientific

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<sup>141</sup> Rex Blair, "Emerging Technologies from the Army-Funded Institute for Soldier Nanotechnologies" (April 4, 2007), <https://apps.dtic.mil/dtic/tr/fulltext/u2/1011334.pdf>.

knowledge, they devised ways to shift time-critical communications into non-visual channels, learning from Major Blair’s combat experience that audio and haptic feedback can reduce overload. ISN Military Liaison Lieutenant Colonel Charles Dean coached the team, describing infantry soldiers’ operational environment, and introduced the team to soldiers at Natick Soldier Center. The team solved problems on their way to winning an award and forming themselves into the small business called RallyPoint.

Frame of Reference	Orientation		Desired Direction	Resulting Message
	Originator	Receiver		
1. Originator				“To My Front!”
2. Receiver				“To Your Left!”
3. Absolute				“Southwest!”



*Figure 24. Communicating Direction Information, Forrest Liau et al, US Patent 7,460,011 B1, 2 December 2008. Image from “Emerging Technologies from the Army-Funded Institute for Soldier Nanotechnologies,” presented by Army Major Rex Blair, NDIA Pacific Operational Science & Technology Conference, Honolulu, Hawaii, 4 April 2007. (See Fair Use Determination)*

The team translated available materials into a novel configuration to solve problems soldiers experienced during operations. Without external funding or incentives such as course credit, the undergraduates voluntarily worked on their own time, nights and weekends. Together the team designed and rapidly developed an innovative, cheap prototype. They used their consumer knowledge to solve materials sourcing, purchasing flexible sensors on eBay. They bidirectionally enrolled military mentors Blair and Dean to understand soldiers’ likely cognitive loads on the battlefield. They realigned computer

input signals, instead of relying on reading and typing, to translate standard military hand gestures to communicate through computers.

A truly novel aspect of their project was inspired by the combat confusion experienced in the 1993 Black Hawk Down incident in Somalia. Soldiers needing rescue from a hostile crowd were misoriented, and the reinforcements spent precious time correcting for directional confusion. To avoid this type of problem, the student team worked closely with the Army officers earning MIT master's degrees to learn how standard military hand gestures for communications. Team members traveled to Fort Polk, Louisiana to observe soldiers in Joint Readiness Training Center military operations. Based on a rich understanding of military operations and problem set, the team patented their approach to translating each soldier's relative directional perspective to a locally shared 'true' directional reference. Figure 1 shows how each soldier received instructions, based on his own frame of reference, translated from another person's gestures.

Once the Soldier Design Competition finals were over and RallyPoint received their second prize award with cash prize, the team decided to commercialize their technology. They targeted the Natick Soldier Center's Future Force Warrior Program as technology recipient. The team decided on company structure; incorporated as a business; patented their intellectual property; and successfully competed for and won Army Small Business Innovation Research (SBIR) grants of \$750,000, as well as DARPA program funding.

The team scaled up manufacturing, and began marketing their product, to Army Future Force Warrior research project managers and for dual use by first responders. Fire fighters faced similar confusion in smoky environments with team members facing different directions. The company succeeded in winning funded projects under DARPA

Urban Leader Tactical Response, Awareness & Visualization (ULTRA-Vis) program, as a subcontractor, and demonstrated their technologies to military members at Eglin Air Force Base, Florida. At the same time, co-inventor Forrest Liao graduated and rejoined MIT as a graduate student. As described in Chapter 4, he conducted basic biotech research with ISN Professor Angela Belcher, continuing his development as a focused scientific researcher.

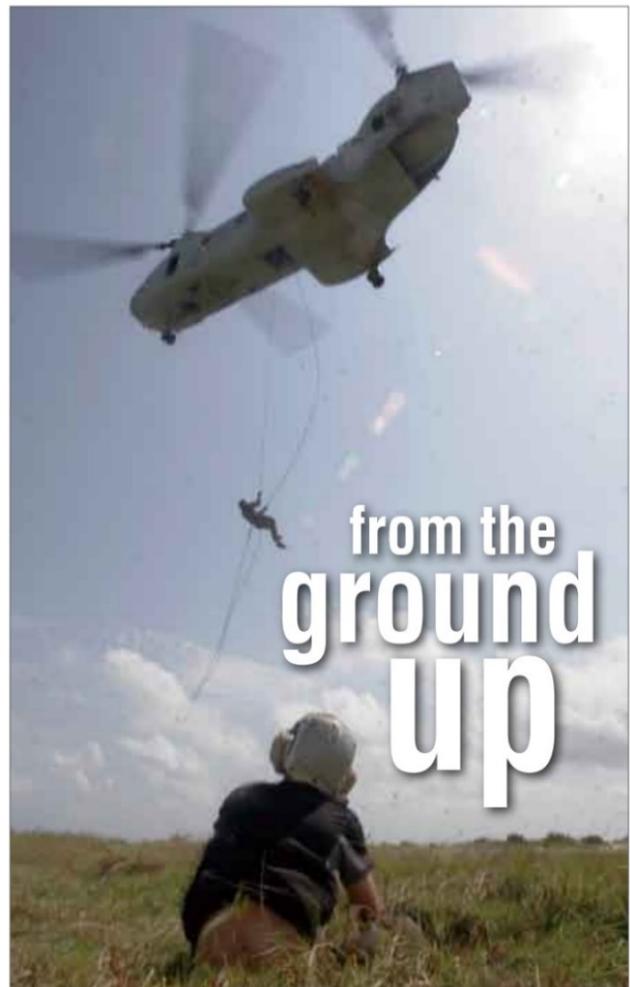
In terms of expanding the ISN's network to military technology users and different networks of military technology development sponsors, RallyPoint represented an unforeseen and radical success. The student team navigated the complexities of winning SBIR awards and DARPA grants while carrying full academic loads as MIT undergraduates, making entrepreneurial success appear easy to outside viewers. The team's abilities to hold together as a small business, while innovating, traveling, meeting new military users and getting feedback, appeared unlikely – a tremendously motivating technology transfer, inspiring students and faculty alike. The undergraduates became the local experts in how to navigate the complexities of Defense systems acquisition in a credible manner, and taught their professors how to do so, inverting the traditional power hierarchy described in Actor-Network Theory.

### **ATLAS Powered Rope Ascender**

In the 2004-2005 Soldier Design Competition, Nathan Ball and his teammates designed and developed a 30-pound portable winch that could rapidly lift 250 pounds up a standard rappel rope. The portable lifting device gained media interest as a real-world implementation of a 'Batman belt,' an easily understood descriptor of the novel yet useful device. The student team sought to ease rapidly rappelling up a vertical obstacle, to help

operations for Army and Marine users and emergency first responders. The team networked with users: military mentors, Marines and soldiers in the field, which expanded their design and potential uses. The Army enrolled the talented team of mechanical engineer problem-solvers by sending inventor Nathan Ball with mentor Major Rex Blair to the Pacific Operational Science and Technology Conference in Hawaii in April 2007.

For the student, a free trip to Hawaii gave him exposure to an entirely new network of potential customers. For the Army and ISN, their spokespersons were innovative, creative, hands-on problem solvers who addressed real needs with compelling new technologies. The opportunities to enroll new customers were translated into adoption, through ATLAS powered ascender purchases by Marines, demonstrated in field exercises in Okinawa and Thailand. Fellow students and MIT faculty were impressed by the business success and up-close association of the engineer/designer with technology users. These visits accelerated network enrollment and translation of needs and future applications from technology users to solution designers.



Nathan Ball, co-inventor of the Atlas Power Ascender, watches as a Marine with Marine Medium Helicopter Squadron 262 gets lifted to a helicopter at U-Tapao Royal Thai Airfield May 14. Photo by Lance Cpl. Aaron D. Hostutler

## Marines test new extraction device

*Figure 25. ATLAS Rope Ascender Nathan Ball Observes Marine Operations, Okinawa Marine, 30 May 2008. (See Fair Use Determination)*

Over the intervening decade, the ATLAS customer base expanded to include commercial telephone wire maintainers and other users not originally envisioned. A 2017 National Public Radio interview described these extended uses, including safely restoring electric wires post-hurricane. Nathan Ball described the productive relationships with users and potential users of the ATLAS devices:

Sometimes you come up with a concept and put it out into the world with an initial vision for what it's good for, and how people are going to use it.... Then they come up with new ways to use it. And that's one of the most exciting things about putting something new into the world, is you actually don't know what it might get used for.<sup>142</sup>

In addition to demonstrating student innovation, the ATLAS team experienced bidirectional enrollment to users, and from new users finding new ways to benefit from their creativity.

Like RallyPoint, ATLAS professionalized. The student team patented their intellectual property and formed a firm to produce their devices. They enrolled professional lawyers and accountants to be able to receive federal contract funds; and competed for and won contracts with Army, Marines, Special Forces, and non-military customers.

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<sup>142</sup> Joe Palca, "The Army, The Inventor, and the Surprising Uses of a Batman Machine" (Washington, DC: National Public Radio, September 5, 2017), <https://www.npr.org/2017/09/05/545481011/the-army-the-inventor-and-the-surprising-uses-of-a-batman-machine>.



# The ATLAS Powered Rope Ascender



Enabling Rapid Vertical Mobility



## Student Technology Transition



- Fall 2004: Team ATLAS Enters *MIT-ISN Soldier Design Competition*
- Spring 2005: Working Prototype wins 3<sup>rd</sup> Place  
*Atlas Devices, LLC* Incorporates, files patent
- Summer 2005: Demo at Infantry Center at Ft. Benning
- Since then: 3 more patents, Partnerships,  
further iterations, and contract with US Army  
Rapid Equipping Force

nate.ball@atlasdevices.com

Mar 2007

*Figure 26: Atlas Powered Rope Ascender: Student Technology Transition. "Emerging Technologies from the Army-Funded Institute for Soldier Nanotechnologies," presented by Army Major Rex Blair, NDIA Pacific Operational Science & Technology Conference, Honolulu, Hawaii, 4 April 2007. (See Fair Use Determination)*

Inventing the device garnered co-inventor Nathan Ball the Lemelson-MIT innovation award and \$30,000 prize – significant money for a student. Ball leveraged these experiences to co-host a PBS television show encouraging science and engineering rapid prototyping for high school teams, enrolling students early into the STEM community.

Both teams demonstrated significantly innovative approaches to practical problems soldiers faced. Both reviewed operational failures with their military mentors – for RallyPoint, communications confusion demonstrated in the Black Hawk Down event; and for ATLAS, the need for rapid, portable evacuation in Hurricane Katrina rescue

operations. Both teams discussed options for establishing their teams and businesses with the MIT entrepreneurial ecosystem, MIT Venture Mentoring Service and MIT Sloan business students. Both teams considered the MIT \$50K Entrepreneurship Competition. The RallyPoint device was targeted to fit as a component in an integrated battlesuit, while the ATLAS powered rope ascender was a completely separate piece of kit that anyone could use with little training. Both small businesses improved their devices with users and business acumen as they won and performed on government contracts.

The RallyPoint team's close association with the Army Future Combat Systems and its Future Force Warrior soldier subprogram. Facing rising costs of the wars and Hurricane Katrina recovery costs in 2005, the Department of Defense reduced, then cancelled Future Combat Systems. RallyPoint and other technologies targeted at the major system scrambled to find different technology transfer avenues. This conundrum confronted the ISN core research, as well as the next Soldier Design Competition team.

### **Transitioning Brain Sensor Technology to the Military**

STS scholars consider how different kinds of credibility assessments may help or hinder technology transfer. The third case study on sensors to detect Traumatic Brain Injury (TBI) demonstrates many issues. The soldier helmet-mounted brain sensor prototype from ISN biotech researcher Army Major Luis Alvarez and his team won an award in the April 2007 Soldier Design Competition. Afterwards, the team briefed the Army's second highest-ranking officer, Vice Chief of Staff General Richard Cody. General Cody charged the Army Acquisition community to procure sensors rapidly, resulting in

July product selection and contracting, November testing, and thousands of sensors deployed into Iraq and Afghanistan starting in January 2008.<sup>143</sup>

Outside viewers might view this example in binary terms, pitting creative, early-stage inventors from MIT against bureaucratic, risk-averse Acquisition specialists in the Army. Practitioners would view this situation in more complex, nuanced terms, described next. The loss of the major Army technology integration platform when Future Combat Systems ended similarly affected many innovative technology insertion plans.

Clearly, a key driver of this acquisition success was decisive engagement by senior champion General Cody, who dramatically mobilized Army members. The sensor procurement also catalyzed Army-funded brain injury research, involving ISN Associate Director Professor Raúl Radovitzky and his computational science modeling team. The ISN served as a platform for rapidly expanding the brain research community, engaging researchers nationwide to explore many approaches to understand and address complex TBI problems.

### ***Urgent Operational Need: Traumatic Brain Injury***

With combat operations increasingly intense in Iraq and Afghanistan, Army leaders searched widely for innovations to reduce harm and improve soldier protection. Increasing incidence of TBI raised this concern acutely. Ironically, the serious injuries that in previous wars would have killed soldiers were now survivable, due to greatly improved protective gear and timely medical evacuation shortly after injury.

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<sup>143</sup> Donna Miles, "New Helmet Sensors to Measure Blast Impact," *US Army News*, January 8, 2008, [https://www.army.mil/article/6909/new\\_helmet\\_sensors\\_to\\_measure\\_blast\\_impact](https://www.army.mil/article/6909/new_helmet_sensors_to_measure_blast_impact).

Research led by DARPA program manager and Army neuro-intensive care specialist Colonel Geoffrey Ling (M.D. and PhD) characterized expanding TBI exposures. Historically, TBI resulted from penetrating injuries or closed head injuries caused by impact; explosive blast emerged as a new TBI vector: “During the conflicts of the Global War on Terror ... Operation Enduring Freedom (OEF) in Afghanistan and Operation Iraqi Freedom (OIF), there have been over a quarter of a million diagnosed cases of ...TBI. The vast majority are due to explosive blast... (which) has unique features....”<sup>144</sup> The Defense and Veterans Brain Injury Center (dvbic.dcoe.mil) reported on the scale of TBI across the Department of Defense: “From 2000 through 2010, 202,281 service members were diagnosed with TBI. The majority of these injuries (77 percent) are classified as mild TBI ... concussion.”<sup>145</sup> The scale of these survivable injuries confounded traditional post-conflict predictions of the long-term injured veterans population.

### ***Student Prototype Soldier Brain Sensors***

Army Uniformed Scientist and MIT biochemistry PhD student Major Luis Alvarez first competed in 2006. His team included MIT undergraduates, per Soldier Design Competition rules. The team created a prototype health status monitor: a hydration sensor designed for an integrated soldier battlesuit, targeting the Future Force Warrior ensemble.

In 2007, Major Alvarez again assembled a team that included MIT undergraduates to design a different physiological monitor. The proposed Blast Dosimeter and Analysis System would track each soldier’s exposure to explosive blast events, creating a

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<sup>144</sup> John Magnuson, Fabio Leonessa, and Geoffrey S. F. Ling, “Neuropathology of Explosive Blast Traumatic Brain Injury,” *Current Neurology and Neuroscience Reports* 12, no. 5 (October 2012): 570–79, <https://doi.org/10.1007/s11910-012-0303-6>.

<sup>145</sup> Kimberly S Meyer and Michael S. Jaffee, “Overview of Traumatic Brain Injury Within the Department of Defense” (2011), from: <https://www.ncbi.nlm.nih.gov/books/NBK209328/>.

dosimeter to measure repeated blast effects. Major Alvarez drew on his own combat experiences in Baghdad when an improvised bomb blew up his vehicle. This experience reinforced the need to capture data on soldier closed head injuries, even for people not medically evacuated. The team sought to detect the types of explosive blasts seen in Iraq and Afghanistan. In combat operations, soldiers faced repeated attacks by rapidly constructed improvised explosive devices (IEDs), daisy-chained to explode sequentially. As a result, many soldiers experienced blasts, and were diagnosed with repeated TBI events. Soldiers diagnosed with mild TBI would return to combat without treatment: these subtle injuries were difficult to detect. Army senior leaders declared TBI a most troubling war injury, affecting soldiers for years, and urgently sought solutions.

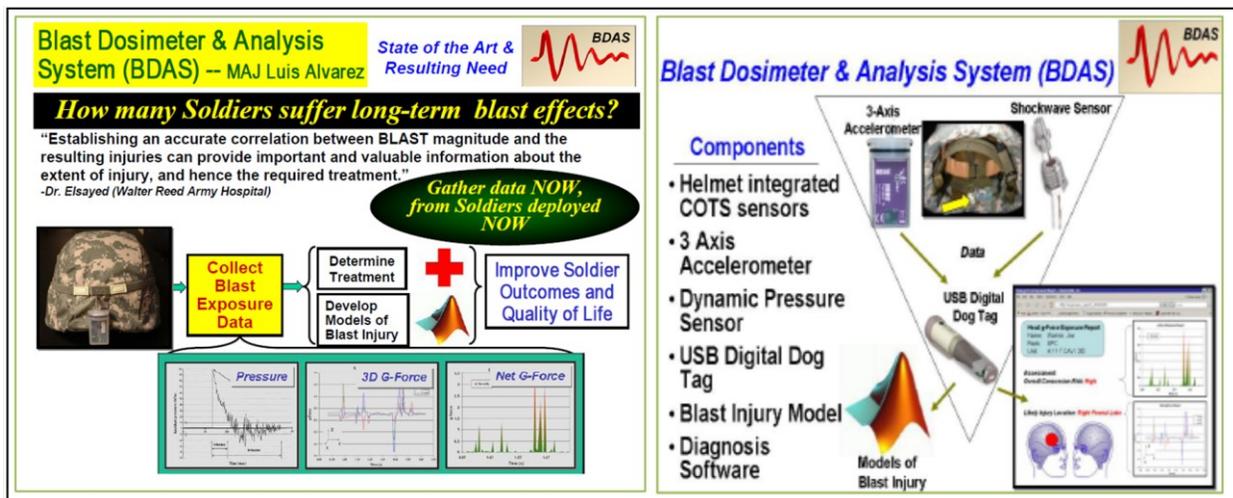


Figure 27. Blast Dosimeter and Analysis System, by Major Luis Alvarez, Army Uniformed Scientist / MIT PhD Candidate, ISN Soldier Design Competition, Cambridge, MA, 10 April 2007. (See Fair Use Determination)

Major Alvarez and team sought to provide a quick response prototype sensor, using the Soldier Design Competition to help soldiers immediately. Soldiers were challenged in tracking the blast event occurrences and effects. Providing an external sensor could be more effective than requiring each person to keep written notes of when

various IED blast events occurred, and trying to remember symptoms afterward. When medically evacuated, people recovering from an immediate blast injury were unable to describe or document their prior blast experiences or TBI history. The blast dosimeter design would provide a record not by soldiers, but for soldiers. Veterans who left active duty were unable to document brain injuries received in combat. A sensor combined with record could inform current medical treatments and future veteran-status health care.

The prototype blast dose measurement system won a Soldier Design Competition award. The prototype functioned as a blast dosimeter, combining 3-axis accelerometer and shockwave sensor to create a digital dog tag mounted on the helmet. This system could meet three unmet needs: provide users with information for immediate treatment; longitudinally track blasts received over time; and track population-level effects. The third benefit proved helpful to medical treatment and brain research, with a dataset documenting characteristics of blast impacts affecting soldiers. The data enabled medical researchers to shape future medical treatment, brain research, and equipment design.

### ***Army Leader Engagement***

During the 2007 Soldier Design Competition finals, senior Army judges understood the potential usefulness of TBI sensors for combat soldiers. In April 2007, Professor Radovitzky briefed 4-star General Cody on ISN computational models to simulate blast-brain interactions, as well as the student prototype blast dosimeter. General Cody directed that the Army Acquisition community initiate rapid procurement of prototype sensors to be mounted on soldier helmets to detect mild TBI.

## ***Army Acquisition of Helmet Brain Sensors***

The Army Acquisition community moved into high gear. The Program Executive Office that purchased soldier equipment (PEO Soldier) released a contractual Request for Proposal (RFP) seeking sources that could rapidly manufacture soldier helmet mounted brain sensors. Unfortunately, this transition from the academic innovation center to the Army's bureaucratic acquisition system did not occur smoothly. The major constraint that shaped the sensor procurement resulted from how acquisition managers are judged: procurements for defined requirements must meet cost, schedule, and performance goals for the acquired capabilities. The acquisition program managers procuring the helmet-mounted brain sensor sought a well-defined and mature design for a battery-powered sensor that detects not blast, but the acceleration of the soldier's head. Blast is difficult to measure, with non-linear inputs from many directions. Head movement can be measured in terms of forward-back, up-down, and side-to-side. The second change resulted from the degree of integration with information systems. Instead of having an integrated device that by itself tracks soldier blast exposure, as a dosimeter would, the acquisition program managers sought to separate the functions, scaling up to fit into the enterprise-level information technology installed base. The proposed integrated sensor-tracking system would require extensive engineering to design, test, deploy, and secure the data systems needed to capture sensor data. Acquisition practitioners sought to meet senior leader urgent requirements by separating acceleration detection from tracking, the process of recording each person's event history. This design choice enabled sensor data to be captured on a soldier helmet-mounted sensor. Event data was downloaded from each helmet periodically, at mealtimes or weekly, and data later input

into individual soldier electronic health records in batches. The combined event data streams added to a classified database of battlefield events, giving a population-based understanding of types of injuries confronting the soldiers in combat, where and when.

### ***Prototype Sensor Procurements***

The July 2007 source selection led to procurement of thousands of prototype sensors. PEO Soldier bought two configurations. The inside-the-helmet configuration was closer to the skull, increasing accuracy of data compared to real movement, but introduced risk of damage if hit by a projectile (bullet, bomb shrapnel). Either the sensor or battery could shatter, turning fragments into spall, adding penetrating wounds to a TBI. The external sensor positioned the battery and sensor farther from the skull. This positioning was safer, reducing the risk of spall, but less accurate in capturing brain motion within the skull, beneath hair, inside a helmet.



*Figure 28. PEO Soldier's Major William Schaffer displays a Kevlar helmet with externally mounted sensor to collect blast data, at left; the sensor, in center; and at right, the internally mounted helmet sensor. Army News, Fort Belvoir, VA, 7 January 2008. (See Fair Use Determination)*

In November 2007, infantry soldiers at Fort Benning, Georgia tested both types of prototype brain sensors under simulated combat operations. The operational test feedback increased confidence that the sensors worked effectively, and so thousands of soldiers from two units were issued sensors beginning in January 2008. PEO Soldier equipped the 101<sup>st</sup> Airborne Division's Kevlar helmets with externally mounted sensors to collect blast data in Afghanistan. PEO Soldier issued the internally mounted variant to 4th Infantry Division soldiers deploying to Iraq. The sensors selected were chosen based on ability to be produced rapidly; by separating the sensing from the data system, the design was simpler. The sensors needed to be interoperable with existing deployed computer information systems and tactical network communications, which were not the 'clean start' envisioned with the Future Force Warrior but instead were a complex and messy set of computer infrastructures which varied considerably across the combat zones. The sensors had to be reliable to withstand months of operations, with minimal maintenance and intervention required.

These design requirements for simple design, interoperability, and reliability did not match the novel student prototype based on a never-before-seen design. The features highlighted by the Army Acquisition community to justify their procurement choice emphasized these reliability aspects, not the innovative approaches that were favored by the MIT research community; different logics for technology selection apply to the two networked groups. For the externally helmet-mounted sensors going to the 101<sup>st</sup> Airborne Division, key features included "...a hardened casing that is covered by a camouflage flap. It weighs about 6 ounces and has a six-month battery life... (and) enough memory

to store data on 527 events.”<sup>146</sup> In contrast, soldiers deploying in the 4<sup>th</sup> Infantry Division had an internal sensor, mounted in the padding inside the top of the helmet with a rechargeable battery. Both types of sensors were downloaded by connecting to a USB port on a computer managed by a forward support team from PEO Soldier, stationed at dining facilities where soldiers gathered for meals. To support the sensors, PEO Soldier had to design the database, ensure system interfaces with the classified event database and the unclassified health records, train and deploy PEO Soldier representatives into combat.

During periods of combat operations, operational data were gathered on both variants to track soldier brain injuries. The results of the combat operations documented in the classified Joint Trauma Analysis and Prevention of Injury in Combat (JTAPIC) database. (Researchers who wanted to participate in analysis of these unique data elements had to partner with Army researchers who were authorized access to the classified data.) PEO Soldier purchased and fielded helmet mounted sensors for years. Five years later, a second-generation device was procured based on the feedback from the first-generation devices. For more than a decade soldiers used these sensors to detect TBI events.

### **From Brain Sensor Prototypes to the Brain Research Portfolio**

From an Army Acquisition perspective, soldier helmet mounted brain sensors were viewed as a success, rapidly accelerating the newest technology from the lab to the field

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<sup>146</sup> Miles, “New Helmet Sensors to Measure Blast Impact.”

to save soldiers' lives and improve long-term health. The brain sensors also highlighted the need for additional new knowledge on brain injury causes, observed effect, and specifically whether blast could cause trauma. Brain researchers focused on car accidents and aeromedical impacts, when helicopters crash out of the sky, had documented different types of brain injuries. However, the blasts caused by explosives became a widely encountered threat in combat for people who fought insurgent operations in Iraq and Afghanistan. In response, the Army accelerated many research efforts to define mild TBI and to determine whether non-penetrating events caused by blast pressure waves could cause persistent brain injury. A large research portfolio emerged with several different research projects at universities around the United States researching different aspects of brain injury.

With these academic brain research efforts, paralleling the sensor acquisition, the ISN team created and launched large collaborative community discussions about blast and brain injury, seeking to increase knowledge about non-penetrative brain injuries. The ISN sponsored nationwide phone conferences for TBI researchers: exchanging current research information; and describing brain injury research efforts included simulation of brain injuries, cellular biomarkers of brain injuries, detection methodologies for injury causing events, and improved materials and equipment designs to reduce potential effects of blast and ballistic events. The diverse interdisciplinary community included 160 academics and Army researchers representing many disciplines and sub-specialties,

Army user representatives (Translators), Army medical experts, and representatives from related communities, listed in Table 4.

*Table 4: Soldier Blast Research Group, 2007*

**Academia:**

MIT Institute for Soldier Nanotechnologies (ISN), Cambridge, MA  
MIT Biological Engineering Department, Cambridge, MA  
University of Virginia (UVA) Center for Applied Biomechanics, Charlottesville, VA

**Army, Defense, Veterans Medical:**

Office of the Surgeon General (OTSG), Washington, DC  
Army Medical Department (AMEDD) Field Office, Ft Sam Houston, TX  
Defense & Veterans Brain Injury Center (DVBIC), Washington, DC  
US Army Aeromedical Research Laboratory (USAARL), Fort Rucker, AL  
US Army Medical Research & Materiel Command (MRMC), Ft Detrick, MD  
US Army Natick Soldier Research, Development, Engineering Center (RDEC), Natick, MA  
US Army Rapid Equipping Force (REF), Fort Belvoir, VA  
US Army Research Institute on Environmental Medicine (USARIEM), Natick, MA

**Army Research and Development:**

Army Research Laboratory (ARL)  
- Headquarters (ARL-HQ), Adelphi, MD  
- Human Research and Engineering Directorate (ARL HRED), Adelphi, MD  
- Sensors and Electron Devices Directorate (ARL-SEDD), Adelphi, MD  
- Survivability/Lethality Analysis Directorate (ARL-SLAD), Aberdeen Proving Ground, MD  
- Weapons and Materials Research Directorate (ARL-WMRD), APG, MD  
Army Research Office (ARO) Blast Research, Raleigh, NC  
US Army Natick Soldier Research, Development, Engineering Center (SRDEC), Natick, MA  
US Army Tank-automotive & Armaments RDEC (TARDEC), Warren, MI

**Army and Marine Corps Acquisition:**

Program Executive Officer (PEO) Soldier, Ft Belvoir, VA  
- Product Manager, Soldier Survivability (PM SSV), Fort Belvoir, VA  
- Program Manager, Soldier Equipment (PM SEQ), Fort Belvoir, VA  
Joint IED Defeat Organization (JIEDDO), Fort Belvoir, VA  
US Army Rapid Equipping Force (REF), Fort Belvoir, VA  
US Marine Corps Systems Command (MARCORSYSCOM), Quantico, VA

**Army User Representatives:**

US Army Infantry Center (USAIC), Fort Benning, GA

## Analysis

These case studies demonstrate messy, contingent, adaptive responses to soldier challenges, resulting in unforeseen avenues for enrollment to and from the military communities of users, as well as the separate Acquisition and S&T intermediaries who seek technologies to meet user needs. The student teams enrolled each other and built out in snowball fashion, adding to their core and divesting where the new network participants could not be helpful. The knowledge gained by insiders who were present during the earliest phases of these entrepreneurial ventures is not captured in the publicly accessible information, but significant insights can be gained in studying these student teams as they translated knowledge into capabilities and used user feedback to shape the next iterations.

## Longer Term Impacts

There were unforecasted long-term impacts, with the expanded brain research community. The different community members followed many approaches to understand and address complex TBI problems. Brain research teams engaged in major collaborations and publications.<sup>147</sup> Associate Director Professor Radovitzky led blast-brain injury interdisciplinary research projects under Team 3. These research initiatives were detailed in the Army's 2008 report to Congress about brain research initiatives, which reflects a substantial fan-out of brain research modeling, biomarkers, sensors, and

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<sup>147</sup> M. K. Nyein et al., "In Silico Investigation of Intracranial Blast Mitigation with Relevance to Military Traumatic Brain Injury," *Proceedings of the National Academy of Sciences* 107, no. 48 (November 30, 2010): 20703–8, <https://doi.org/10.1073/pnas.1014786107>.

medical research.<sup>148</sup> The Defense and Veterans Brain Injury Center received significant increases in funding and significant increases in awareness, both inside and outside the Department of Defense. The secondary benefit benefits of the brain injury research spread rapidly to inform and accelerate research on sports brain injuries. In 2012, Army Chief of Staff 4-star General Ray Odierno signed an agreement with National Football League commissioner Roger Goodell to raise awareness of TBI and seek ways to prevent and mitigate these injuries.<sup>149</sup> Both parties researched new helmet designs to mitigate different modes of shock and impact, to better protect wearers' brains.

### **Impacts on Student Innovation**

Despite successes in rapidly acquiring and deploying sensors to detect immediate challenges, these advancements also brought liabilities and ethical considerations. If not for having soldiers in combat who repeatedly deployed into harm's way, the knowledge gained from people injured in long-duration conflict operations would not exist. Another ethical issue arose from the rapid acquisition of brain sensors: student participants of the Soldier Design Competition felt uncertainty about how their ideas would be treated by the Army. Major Alvarez generated the concepts of the blast dosimeter, but what the Army ultimately procured was not based on his idea. The participants in the Acquisition community would describe themselves as constrained by structural rules; needs for interoperability with combat-zone computer and communications infrastructure; and reliability, manufacturability, and dependability in cost, schedule, and performance. The

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<sup>148</sup> US Department of Defense, "2008 Annual Report to Congress: Efforts and Programs of the Department of Defense Relating to the Prevention, Mitigation, and Treatment of Blast Injuries" (Washington, DC, October 2008), <http://www.dtic.mil/dtic/tr/fulltext/u2/a506522.pdf>.

<sup>149</sup> US Army, "Army Chief of Staff, NFL Commissioner Sign Letter Formalizing TBI Initiative," August 30, 2012, <https://www.army.mil/article/86506/>.

MIT innovators were introducing a novel device, which had not been produced at scale. The SDC team targeted the platform of an integrated battlesuit, planned by Natick Soldier Center to support the Future Force Warrior program in 2020 and beyond -- not available for current operations. Faced with the requirement to scale up device procurement rapidly to equip thousands of soldiers in two combat theaters, PEO Soldier decomposed the requirements suggested by the prototype device. They could not assess, due to lack of research, how much dosage of blast would be harmful to an individual. As a result, PEO Soldier set the device requirements to measure acceleration, not to measure blast. Instead of tracking cumulative doses, the selected devices only tracked individual events; the cumulative analysis occurred in off-soldier combat event databases. The short timeline to solicit sources, select offerors, and have devices manufactured in order to equip thousands of soldiers led the Army Acquisition team to a lower risk approach. This risk-reduced approach used more conventional sensors than the prototype blast dosimeter system that needed to be integrated into supporting computer information systems and might require an unknown number of replacements for any time period.

While these structural constraints made sense to individuals and firms with experience in the bureaucratic processes used for Army Acquisition and industrial production, innovators among the broader ISN community at all career levels, from undergraduates to professors, were perturbed by the non-implementation of the winning Soldier Design Competition design. Given the ISN's early controversy with intellectual property, when the ISN proposal cover art used Lai Brothers intellectual property without permission, the ISN needed to maintain strong support for intellectual property rights. Major Alvarez presented a specifically challenging instance, representing multiple groups

in one person. As an Army officer attending advanced civil schooling, he received Army salary. No specific provisions were made for inventions of Army officers with dual roles as Uniformed Army Scientists and students earning degrees, who worked on these innovative prototypes in their free time, nights, and weekends. This particular intersection of networks in a single individual had not been considered in formulating the Soldier Design Competition rules. Both the ISN and the Army had to resolve this lack of clarity on intellectual property rights, to encourage MIT undergraduates, graduates, and professors to be willing to work with Army officers, without fear that collaboration would impinge on the future intellectual property rights of MIT innovators.

Although no resolution is publicly documented for external viewers, the Army and MIT appeared to clarify this issue. Major Alvarez continued to work as an ISN researcher, collaborating with MacArthur grant awardee and ISN faculty, Professor Linda Griffith. The collaboration was productive, enabling Major Alvarez to earn his PhD, and contributing new designs in extensions on the 'liver on a chip' pharmaceutical testers which Professor Griffith pioneered.

In addition to the productive research relationship, the ISN Soldier Design Competition web page specifically called out Major Alvarez for his innovative soldier helmet brain sensor. In this way, Major Alvarez gained social capital as an innovator who catalyzed brain research activities at the ISN, and contributed to the broader Army-wide brain research that benefited soldiers both immediately and over time.

## **Qualitative Analysis**

My quantitative analysis focused on identifying each student prototyping team's initial approach to transition technology. The key question: who was enrollment focus?

Designers crafted prototype technologies or performed the brain research. Users were the end-users of the technologies, such as soldiers, Marines, and emergency first responders. Translators linked Designers and Users, such as military technologists who perform technology search and describe technologies to users or procure example technologies for user assessments. The symbols below indicate the larger circle indicating area of focus on one of the three categories, Designers, Translators, or Users. Each of the student prototype teams focused differently.

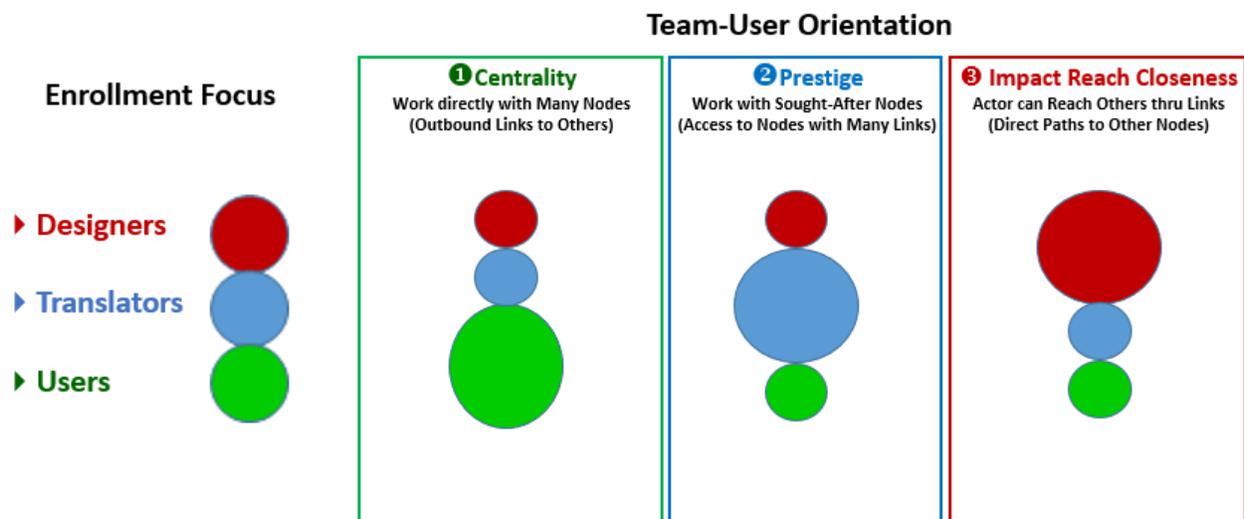


Figure 29. Team-User Orientation

The quantitative measures described in Appendix A can be used for complementary analysis. Centrality is aligned with teams who work with many nodes, demonstrated by an actor-network diagram with many outbound links to others. Prestige is demonstrated by a team who works to access nodes with many outbound links, resulting in work with sought-after nodes (analyzed by Page Rank Prestige analytics). Impact Reach Closeness is seen in a team with direct paths to other nodes, enabling the student teams to reach others through network links (analyzed with Impact Reach Closeness Centrality measures).

Each of the three student teams discussed in this chapter demonstrated a different Team-User Orientation. RallyPoint focused on **Users**, demonstrating an approach of centrality by first targeting Users in their trips to meet with soldiers at field training sites including Fort Polk, Louisiana. As a result of this deep understanding of the user community, the student team engaged effectively with the Natick Soldier R&D center scientists, researchers, and technologists. The second team, ATLAS, first targeted **Translators** at the April 2007 PACOM S&T conference, meeting technology scouts linked with Army, Navy, Marine, and first responder communities across the Pacific theater. This network enrollment with Translators led to many organizations purchasing ATLAS Powered Rope Ascenders. Other Translators became aware of this capability, and reached out through earliest customers, showing their own links to strongly-linked actors. The final team, focused on the Blast Dosimeter concept, oriented to **Designers**. Targets were both military equipment designers, particularly helmet and helmet-mounted gear designers, and designers of brain research that could use the information output from soldier helmets. The analytic that can measure this approach is the Impact Reach Closeness Centrality, assessing the shortness of paths between the team and the nodes they seek to influence. Each student team demonstrated different approaches to transition their prototype technology, and succeeded in different ways.

## Team-User Orientation

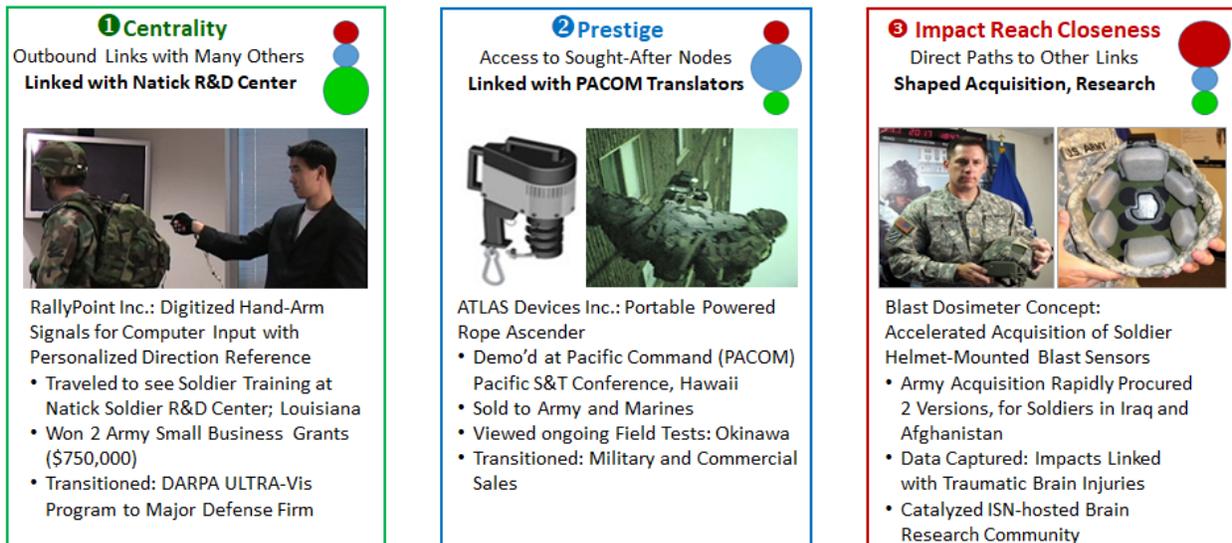


Figure 30. Assessing Student Prototype Teams' Team-User Orientation. Images from "Emerging Technologies from the Army-Funded Institute for Soldier Nanotechnologies," presented by Army Major Rex Blair, NDIA Pacific Operational Science & Technology Conference, Honolulu, Hawaii, 4 April 2007; right image: Army News. (See Fair Use Determination)

As the students fulfilled their roles as members of the ISN research community, each lead working on biomedical capabilities to improve human protection, the students imparted their knowledge of how to transition technologies to their professors. These interactions inverted the traditional hierarchical power structure, where knowledge flows from experienced professor to less-experienced students. Instead, these actor-network enrollments were bi-directional, with knowledge about technology transitions flowing from the experienced student transitioners to their less-experienced professors who were learning how to navigate the Army procurement bureaucratic processes. The students and professors participated in two separate actor-networks at the same time. The power and knowledge flows depended on which network each of the actors was fulfilling at a given time, based on topic. While the networks were separable and oriented to transition different technologies, the actors within should be able to discern clearly in which roles

and relations they are operating. As ISN research technology transitions mature to fruition, likely collisions between the actor-networks increases, creating opportunities for tensions and misaligned incentives and actions between students and faculty.

## Conclusions

Prototyping efforts from the Soldier Design Competition provided important linkages, building networks between students, faculty, business partners, Army scientists and mentors, and Army leaders. Early successes showed how innovative small teams could substantially accelerate expected timelines and solve integration problems creatively and quickly. Army Acquisition was primed to work faster to spread new innovations across Army formations. The prototypes spurred new research in brain injury causes and remediation, as well as new designs for helmets, protective gear, and new materials to improve human protection. By providing prototype capabilities that could enhance the capabilities of emergency first responders, enhancing communications at a distance and providing portable lift, early visions of dual military-civilian use technologies were materialized in real products. Prototypes gave hundreds of ISN visitors capabilities they could understand, while learning about futuristic nanotechnologies.

For STS theory, these student prototype teams suggest modification of the Actor-Network Theory concept of enrollment. Instead of ANT's primarily top-down enrollment, student teams inverted the traditional power hierarchies as they taught their professors how to connect with and operate effectively within the complex Army and Defense acquisition systems. Expertise was built from the bottom up, as the students navigated both formal Acquisition programs, such as Future Force Warrior program by RallyPoint, and more ad hoc systems, such as the Rapid Equipping Force purchases of ATLAS

powered rope ascenders and the rapid-acquisition efforts of PEO Soldier to procure soldier helmet-mounted brain sensors. The bi-directionality of enrollment between MIT innovative product designers and potential users inside the military and beyond demonstrates a new degree of democratization of innovation and challenges traditional ANT views. The brain research community catalyzed by the brain dosimeter prototype expanded reliance on traditionally non-expert, bottom-up information, relying on the first-person experiences of TBI-impacted soldiers and veterans. Instead of patients receiving treatment, these wounded warriors became subject matter experts, sharing knowledge with researchers.

## Chapter 7.

### Conclusions and Future Research

#### STS Impact

My research illustrates a historical set of actor-network case studies. I detailed **what** these actors did in creating nanotechnologies for transition to users, and **how** they did so. These emergent actor networks operationalized translation and used enrollment to create transition-focused research networks. These networks are nested at multiple levels: small team, research focus team; ISN focus area; MIT department research focus areas; partner- and customer-focused networks. As Latour described in 2011, each actor can have multiple networks as attributes – each actor plays multiple roles in the community in the same time period. These actor-networks demonstrated dynamics described in current STS Actor-Network Theory, such as Law's heterogeneous engineering and enrollment of human and non-human actors.

A significant and novel finding was the **bi-directional enrollment** demonstrated by student prototyping teams. Students learned and taught their professors how to interact with Army acquisition practitioners; patent and contract lawyers; accountants; venture funders; marketers; and potential customers to be enrolled into purchasing and co-creating new uses. Simultaneously, professors taught the students nanoscience and biomedical engineering. Although no public records describe tensions resulting from these simultaneous power dynamics, observers can intuit that challenges arise.

The data-driven quantitative analytic methodologies I describe can be used in concert with the qualitative analyses to identify structure and dynamics of actors in networks, along with the specific details to ground these actors and activities in context.

## Overview of the ISN

My research provides a unique window on a new research institute at the dawn of the twenty-first century. The origins of the ISN included aspiration and controversy. Ultimately, the first five-year contract enrolled many researchers at MIT and the Army, industry partners, and translated influence to cause 'action at a distance' through inscriptions of publications, products and processes. For the Department of Defense, the ISN proved to be a robust 'mecca,' an obligatory center visited by hundreds of people each year: potential partners in academia and industry, and Army S&T, innovation, and user communities. Following the goals of *Science – The Endless Frontier*, this center did create basic science that translated to new knowledge, able to improve health of soldiers and people in emergencies, created jobs, and trained people in STEM.

The center was not without controversy. The early missteps, using Radix graphic art without permission of the authors, led to chastisement by *Science* journal and resulted in public apology. The early error appeared to result in correction: strong and public reinforcement of the value of respecting intellectual property rights. An unforecasted result of the significant media awareness of the controversy was that the Internet Archive captured many web pages from the ISN web site. More than a decade later, these screen captures allow analysts in 2019 to observe snapshots of the research project summaries as they changed over time. Qualitative and quantitative analytics revealed the emergence and ending of various projects, and enable analysts to discern which actor-networks contributed during the ISN's initial era.

## Conclusions by Case

### 6.0 Creating the Institute

Founding Director Thomas created the ISN using enrollment methods. The inclusion of professors at all phases of their careers created a far-ranging research portfolio, varying from 'blue sky' fundamental science, to 'green space' engineered products and processes. My quantitative portfolio analysis methodology can provide useful ways to understand the positioning and evolution of the research projects, and how the teams partnered both to advance science and to create nanotechnologies for transition to users. An unforeseen success in enrollment resulted from the establishment of the Soldier Design Competition, which enrolled MIT undergraduates into the actor-networks of the ISN. The student teams volunteered their own time and resources, without academic credit, to learn about real soldier problems, create functional prototypes, and present to panels of judges within 6 months. The translations from this competition involved not only the students, but also the judges, from Army, MIT and West Point, and industry. An unexpected enrollment avenue opened to the Army mentors, affiliated with Army S&T and innovation centers across America. Normally, these people would have received a written description about emerging research once a year, and would have to work to gain more information and become involved. The Soldier Design Competition created a low-risk, easy engagement with bright young students, creating a simple yet effective means of interaction which mutually enrolled Army and ISN people together. Students benefited from having mentors to discuss their proposals. In concept, teams could receive non-public feedback on projects which might be redundant, unsafe, or difficult to market to military or civilian customers. The competition created

opportunities to bring together many participants from Army, MIT and West Point, and industry in social events which provided opportunities for ISN graduate students to present research at poster sessions. In addition, prior year teams could demonstrate prototypes and describe their current entrepreneurial progress. This seemingly simple annual competition transformed the paths of enrollment and created both enthusiastic advocacy and familiarity across organization boundaries which facilitated ISN core research transitions.

### **6.1 Basic Science and Social Networks of Actors**

The basic research and actor-networks involving Professor Belcher translated the people involved to create increasingly capable research teams and research organizations. This operationalization of translation enabled participants to increase both their skills and generative capacity. The qualitative analysis revealed the transformative role Professor Belcher contributed in establishing the Department of Biological Engineering at MIT, which translated a niche hybrid area of emerging study into a validated academic domain. The benefits of being recognized by such innovation prizes as the MacArthur 'genius grant' and the MIT-Lemelson inventiveness prize benefited Professor Belcher directly, and her networked partners indirectly. Both of those prizes are awarded based on recommendations from prior awardees, so receiving the prizes inducts the recipients into positions of influence which are difficult for outsiders to discern. As an alumna, Professor Belcher would be positioned to recommend future recipients.

The functional insights provided by the Belcher intellectual property map from IPVision showed the strong translations to actor-networks far from Boston, and occurring long after the initial discovery was patented. Quantitative analysis indicated which

members of the actor-networks contributed to have the most impact, discernable even in the earliest days of the ISN. The quantitative analysis also revealed the surprisingly strong impact of Professor Linda Griffith as faculty, focused on a 'liver-on-a-chip' biotoxin tester, and PhD student Ki Tae Nam in accelerating new nano/bio capabilities using viruses to self-assemble batteries, electronics, and medical treatments. The boundary-spanning role filled by Dr. Christine Flynn, who moved from University of Texas-Austin to MIT with Professor Belcher, was uncovered using the quantitative social network analytics. The combination of qualitative and quantitative analysis revealed aspects of the dynamics of the basic research actor-networks which would not have been able to be discerned by an outside viewer, either at the time of the research, or in 2019 looking back in time.

## **6.2 Applied Research for Cancer Research and Science Education**

Professor Hammond's leadership in co-founding the ISN and emphasizing the need for outreach and representation by under-represented minorities and women shaped the ISN and her applied research projects. She described new, inclusive modes of collaboration. Her life experiences as a woman of color incentivized her to make explicit the tacit knowledge needed for academic success by diverse people. To 'grow the bench' of future faculty, she trained her own research group and the broader MIT community on the importance of publishing only after strong results were achieved; and specified the need to apply for specific credibility-enhancing grants in time to be ready for tenure decisions. She demonstrated a pattern of publishing both the material invention and the method of application, as seen with her transformative cancer-fighting nanomaterials. This robust publication pattern spreads knowledge more widely, and bolsters the academic productivity record of all co-authors. Learning from Soldier Design Competition

student teams, she also demonstrated the value of learning from Army soldiers and researchers about what problems needed better solutions. Her improved approach to blood clotting addressed issues seen on the battlefield and facing emergency first responders. As a communicator, she created unprecedented direct channels to members of the general public with her TED Talk on cancer fighting nanoparticles, viewed by more than 1.5 million times on TED, plus the public television audience.<sup>150</sup> These new communications opened new avenues to teach and create action at a distance.

Her thoughtful analysis of the challenges facing under-represented minorities at MIT led her to design and implement new approaches for outreach to enroll students at HBCUs who would otherwise have been left behind this new generation of research. She found some mitigations for the difficult policy challenges which constrained funding for HBCUs. In the materials available in 2019, some evidence exists for her catalyzing targeted outreach to those HBCUs, but details are not publicly accessible. The discussion among HBCU leaders challenged by changing Defense research sponsor support. The HBCU leaders described their need for sustained research support, traditionally provided with Mode 1 traditional disciplinary. At the same time, Defense research sponsors were encouraged by policy to support fast-turn, application-focused Mode 2 transdisciplinary science. HBCUs and other less-prestigious research centers may lack sustainable support for students and faculty seeking to establish new areas of research. However, details addressing these needs are difficult for outsiders to detect, and appear unresolved, based on low production of nanotechnology-familiar scientists from HBCUs.

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<sup>150</sup> Boebel, *MIT Infinite History Interview with Paula Hammond, MIT '84, PhD '93*, 2011; Hammond, *TED Talk: A New Superweapon in the Fight against Cancer*, 2015.

### **6.3 Prototype Traumatic Brain Injury (TBI) Sensors and Research**

The MIT student teams who volunteered (without academic credit) to compete in the ISN Soldier Design Competition transformed both enrollment and translation. Results in terms of technology transitions which would have been expected within the first decade occurred within the first year, setting a high bar for the ISN's future. The three student teams highlighted created entirely unforeseen capabilities, which were not anticipated, and created novel paths of enrollment and translation with Army mentors and Army innovation sponsor communities. Each of the three teams was in turn enrolled by the Army, participating in routine events which translated the students' understanding of soldiers and their environments. Visiting actual soldiers in field settings made the customer real for the student teams, who in turn communicated that knowledge with their ISN faculty and graduate student researchers. The prototype-focused teams created new avenues of translation for the research portfolio leaders, particularly Professor Radovitzky with his computational models of the brain-blast interactions resulting from the student team prototype soldier helmet mounted brain sensors.

However, these interactions were not unproblematic. The Army Acquisition community was directed to accelerate procurement and deployment of brain sensors to detect traumatic brain injuries on soldiers deployed to Iraq and Afghanistan. By following policies which favored reliability and producibility, instead of MIT values for inventiveness and novelty, the Army acquired brain sensors which worked from an information enterprise perspective, rather than the novel approach proposed by the student team. The soldiers benefitted from a longitudinal record of potential brain injuries in their health record. The community benefitted from having data captured from real-world incidents to

study for brain research. For student teams, however, the results occurred after the initial five-year contract period of this study, but such a change would at best have cooled enthusiasm and reduced participation among innovative undergraduate students.

## **Summary**

Overall, each of these case studies illuminated different actor-networks and highlighted different kinds of interactions, enrollments, and translations catalyzed by the ISN. STS qualitative analysis complemented by data science quantitative analysis revealed structure and dynamics to an outside viewer that may have been difficult to discern even inside the actor-networks. The Army sponsors found the results beneficial enough to renew the five-year contract twice in the intervening time. These case studies provide a baseline for comparison of follow-on research, and illuminate ways for Army Futures Command and other federal research and innovation sponsors to consider interacting with federal-academic-industry partnerships.

## **Data Archives in the Internet Era**

The Internet Archive provided a unique and helpful set of data that enabled a current-year analyst to see 15-year-old web sites as they had evolved over time. Although not a perfect archive, the availability of any data from the start of the century was an unforeseen boon to the outsider analyst. However, the Internet Archive is a not-for-profit organization which is supported by charitable donations. Such support could stop at any time, causing the potential loss of these archives. Google provides substantial reach to a vast number of publications, including those digitally scanned and accessible via Google Scholar. However, Google is a for-profit firm, whose corporate policies might at any time

cause them to place their vast stores of information behind a paywall, requiring the viewer to pay money for the privilege of access. The government Defense Technical Information Center (dtic.mil) is a military archive, but the collections are spotty, and the interfaces more challenging to search. Data is ephemeral, and no perfect enduring solution to provide long-term public data access exists. Nonetheless, data archives are worth funding by the research sponsor, to ensure that the knowledge created during the sponsored research period can continue to be translated by new scholars.

## **Future Research**

The ISN-Army-Industry research collaboration should be examined during the follow-on research contract periods, to compare performance and outcomes over time and as ISN participants changed. A number of innovative research partnerships spun off out of the ISN, including the cancer research Professors Belcher and Hammond perform at the MIT Koch Institute for Integrative Cancer Research and Yoel Fink's establishment of the Advanced Functional Fabrics of America (<http://go.affoa.org/>) as one of the National Network of Manufacturing Innovation (NNMI) Institutes. A useful analysis could compare the design of these new research activities and the structure of sponsorship assessed in terms of translative capacity from the original ISN. An assessment of the economic impact of the entrepreneurial students and faculty involved in the ISN, compared with the overall impact of MIT entrepreneurs within the same period, might highlight the benefits of the ISN for definable problems and built-in partners in industry and the Army to accelerate translations and technology transitions. In terms of increasing the participation of underrepresented researchers, interview-based analyses could identify what enrollment techniques worked and what do not, in order to shape new programs and inform policies

to increase STEM participation across America. Additional data science and decision support analytics could inform all the research and be used to shape future sponsored research programs. Overall, the lessons learned from the founding era of the ISN should inform the founding era of the Army's newest innovation sponsor activity, the Army Futures Command, to inform Army members of expectations and ways of working among academics and industry affiliated with early-stage scientific research.

The quantitative methodologies can continue to be expanded to include other analytics from data science. Applying the methodologies to other cases traditionally examined using qualitative techniques, including seeking to identify influencers among oncology practitioners or non-nanotechnology product-focused research and development teams, could help identify potential similarities in behavior patterns which either contribute or hinder technology transitioning to the end users. More case study analysis would show under what circumstances the approaches are robust. The social network analytics used on the prototype teams could suggest future diagnostic and prescriptive approaches for other small project teams. The extensions of these approaches may help accelerate technology transition from art to science.

I plan to continue to explore extending STS Actor-Network Theory to address bi-directional enrollment and translation dynamics. The opportunities to accelerate innovation should continue in both understanding how innovation works, and how to operationalize these insights. Both the practitioners and researchers can learn much by bi-directionally enrolling each other, sharing their networks and collaborating to solve human challenges.

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# Appendix A.

## Entity Analytics: Quantitative Social Network Analysis of Research Network

### Overview

Quantitative Social Network Analysis methodologies can help analysts understand the dynamics performed by the entities within an actor-network.<sup>151</sup> Whether the analyst is enmeshed in the network or not, these data-focused analytics can illuminate often subtle distinctions in importance or centrality of one actor compared with others. Core to data science analytics is the dataset used for the analysis. Significant variance in resulting analyses can emerge from small changes to the input dataset. Repeatability requires disclosure of both the dataset and processes used. To perform entity-focused analysis of this biotechnology basic research network around MIT Professor Angela Belcher during the Institute for Soldier Nanotechnologies (ISN) start-up phase from 2002 through 2007, I used a basic six-step analytic process with the dataset detailed in this appendix. First, I provide the steps, and then I discuss the resulting analysis. This approach demonstrates how computational analytics can be used to understand interactions within a basic research-focused actor-network seeking to transition technologies to users.

### The Six-Step Entity-focused Analytic Process

#### ***Step 1: Define activities and entities of interest.***

My research question is: which actor(s) in this early entrepreneurial biotech basic research network had the most impact? Impact is assessed in terms of co-occurrence in

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<sup>151</sup> Butts, "Social Network Analysis."

research publications and ISN-related organizations including start-up businesses. I focused on the biotechnology researchers around Professor Belcher at the ISN. The goal of this analysis is to identify entities who may benefit from investment of resources including links with domain experts to reinforce successful progress, seek to accelerate transitions, and create opportunities to reduce barriers by increasing awareness of the target technology transfer domain and users.

***Step 2: Analyze the network actors and select the initial analytical focus.***

Many researchers at the ISN were focused on the convergence of nano- and biotechnologies to create new technologies to improve human protection. BiomedExpert.com was an early precursor to Google Scholar, listing biotechnologists and their linked networks. I evaluated the challenge of how to sift through the hugely dominant ISN biotech researchers, particularly MIT Institute Professor Robert Langer. Langer's extensive networks from shared publications, patents, and start-up businesses eclipses those of people who are new to MIT or at a more junior level in their career. Given my focus on investing in researchers and teams to accelerate technologies, I used venture capital funding approaches to identify a researcher with a greater degree of potential impact of investment, one who would experience more impact from the same level investment. The constraints on productivity for Professor Langer derive more from availability and capacity throughputs, not investment inputs. After sifting, I identified Professor Belcher as the focus and used a set of Belcher-related publications to provide the seed for my actor-network entity analysis.

***Step 3: Use snowball sampling techniques to build out network actor list of entities.***

To the seed of publications listed, I added institutions to identify actors' relationships, generating a list of entities (nodes) and identified the relationships as links between them. These links of pairs of co-occurring actors formed the basis of the edge list for the network. Weights were used to indicate multiple co-occurrences of activity between 2 entities. The resulting list of tuples (entity1, entity2, weight) provided the edge list for statistical and visual analysis.

***Step 4: Perform data cleansing.***

All data science analyses must implement a strategy for cleansing data – often repeatedly. Adding elements from 'the wild' to a curated dataset may require analysis both to disambiguate and to resolve entities to ensure the described network closely represents the actual actor-network, to provide conceptual validity.<sup>152</sup> Entity disambiguation occurs when two or more entities identified with the same monikers actually represent different entities. In Washington, D.C., context informs entity disambiguation between 'the hill' (a generic rise in the landscape), 'the Hill' (a neighborhood near the Capitol building), and 'the Hill' (a community of legislators who work in Congress). Equally crucial is entity resolution, where data entities identified with two or more monikers actually represent the same real-world actor. For this biotechnology publication dataset, a simultaneous web site listed Belcher-related graduate student SW Lee under two name spellings: 'Seug-Wuk Lee' and 'Seung-Wuk Lee.'" Resolving these

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<sup>152</sup> Kathleen M. Carley, "Validating Computational Models," Center for the Computational Analysis of Social and Organizational Systems (CASOS) (Pittsburgh, PA: Carnegie Mellon University, April 28, 2017), <http://reports-archive.adm.cs.cmu.edu/anon/anon/home/ftp/usr0/ftp/isr2017/CMU-ISR-17-105.pdf>.

two entity names into one to represent the real Seung-Wuk Lee, ensuring data validity, changed the computable dynamics between members of the biotech-related actor network. Fortunately for academic researchers, Google Scholar and other similar sites available now prove useful in resolving published author entities. However, as more scholars with similar names publish, this task will increase in difficulty.

***Step 5: Select analytic tool(s), load data, and iteratively compute statistical measures and visualizations.***

Computational tools for entity-focused social network analysis proliferate, and new candidates emerge daily. Different tools can be compared based on capacity to handle the number of entities being visualized, and number and complexity of relationships being modeled. Other factors include ease of use for the type of analysis being performed, including tradeoffs between algorithms that are pre-instantiated compared with ability to integrate new algorithms, or to change existing algorithms. Visualization depends on number of entities and attributes being modeled. Any large social media network such as LinkedIn or Facebook friendship links could overwhelm a conventional browser-based computational tool. For very large or complex networks, server-side or cloud-hosted analytics of networks could be viewed in the aggregate in the browser, using additional technologies to support 'drill down' functions. For the small network seen here (55 entities), I first used UCINET social network analysis software, developed in 2002.<sup>153</sup> However, due to the diversity of data visualizations offered and rapid millisecond

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<sup>153</sup> Borgatti, Everett, and Freeman, *UCINET for Windows: Software for Social Network Analysis*.

response for computed metrics, I modeled this network using the free, open source SocNetV social network visualization software.<sup>154</sup> For larger networks or future modeling projects, rapidly evolving Python software packages such as NetworkX can be paired with visualization counterpart NXviz.<sup>155</sup> Data science analytics in Python or other languages can also be programmed by developers or analysts trained by instructors; in emerging data science degree or certificate programs; or by leveraging the many available online data science training providers, including massive online learning programs from EdX or Coursera, and data science boot camps such as Datacamp offers. For analyses using visualization and analytics integrating statistical algorithms, I recommend comparing then-current offerings from the computational capabilities emerging from these diverse and evolving communities.

**Step 6: Perform analysis and iterate as needed.**

Once the data is curated and cleansed, perform analysis. Social network visualizations can show structure and different degrees of influence, for a given network. Initial measures for my analysis visualized group structures, showing subgroup cliques and natural divisions with cutpoint diagrams and dendrogram of cliques. The following statistical analytics that show different ways of analyzing connectedness seek to understand each actor's influence within the network: Degree Centrality, Betweenness, and PageRank Prominence. The SocNetV visualizations of these connectedness

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<sup>154</sup> Kalamaras, *Social Network Visualization (SocNetV)*.

<sup>155</sup> Eric Hagberg, Dan Schult, and Pieter Swart, *NetworkX: Python Package for the Creation, Manipulation, and Study of the Structure, Dynamics, and Functions of Complex Networks*, 2002, <https://networkx.github.io>; Eric J. Ma, *NXviz Graph Visualization Package for NetworkX*, 2016, <https://github.com/ericmjl/nxviz>.

measures can vary in layout (radial or layer), to model the sometimes-subtle variations in an entity's prominence within the network. The rapid responsiveness of SocNetV enabled me to pivot rapidly from query to query, iteratively changing the visualizations and scrutinizing the statistics to discern whom within this network may have more importance in the areas examined. Once these analytics are performed, the resulting outputs can serve as foundational inputs to other higher-level or deeper analytics.

## **Performing Quantitative Analysis of Actor Networks**

### ***Step 1: Define activities and entities of interest.***

Social network analysis can indicate the potential capacity of a group as a whole, and of individual actors within a network. These analytics also enable outsiders and concurrent partners to assess the research, and gain some insights into which actors are impacting the effort for a variety of measures. Network influence varies for each actor across a range of roles. The same actor may be a sibling, neighbor, friend, or a group organizer, having different impact for each of the separate but linked networks. The focus of these actors in this ISN-related network is their role in nano-biotechnology-focused basic research, seeking to translate outputs of research into Defense-relevant and marketable technology applications.

### ***Step 2: Analyze and select the initial analytical focus.***

To define the actor-network of interest, analysts must follow the actors' traces – here, starting with publications. To begin, the network should be assessed to determine what actors are exogenous, or outside of a given network analysis. In this instance, my analysis is interested in researchers affiliated with Professor Belcher on biotechnology

research during the start-up phase of the ISN. The now-defunct BiomedExperts web site, which claimed to be the first literature-based scientific social network, was created to increase biomedical research collaborations.<sup>156</sup> The table in Figure 31 below shows publication statistics of four MIT professors who conduct biotechnology research at the ISN in this period, given the delay after research for publications to be released. From these publication statistics, the initial social networks can be computed. This sample (February 2009 to May of 2009) shows numbers of publications for MIT ISN-related Professors Langer, Cima, Hammond and Belcher, and their rate of change.

Computed Network	Publications		Coauthors	2nd Level	3rd Level	Level 3 Increase
<b>Langer, Robert S</b>	8 Feb 2009	<b>424</b>	<b>348</b>	<b>11,269</b>	<b>243,421</b>	<b>8.1%</b>
	8 May 2009	<b>437</b>	<b>361</b>	<b>12,402</b>	<b>263,100</b>	
<a href="http://www.biomedexperts.com/start/PersonDetailPage.aspx?pid=774465">http://www.biomedexperts.com/start/PersonDetailPage.aspx?pid=774465</a>						
<b>Cima, Michael J</b>	8 Feb 2009	<b>27</b>	<b>23</b>	<b>980</b>	<b>31,510</b>	<b>66.5%</b>
	8 May 2009	<b>28</b>	<b>25</b>	<b>1,519</b>	<b>52,463</b>	
<a href="http://www.biomedexperts.com/Start/PersonDetailPage.aspx?pid=245237">http://www.biomedexperts.com/Start/PersonDetailPage.aspx?pid=245237</a>						
<b>Hammond, Paula T</b>	8 Feb 2009	<b>33</b>	<b>27</b>	<b>686</b>	<b>22,931</b>	<b>7.0%</b>
	8 May 2009	<b>35</b>	<b>28</b>	<b>714</b>	<b>24,535</b>	
<a href="http://www.biomedexperts.com/Start/PersonDetailPage.aspx?pid=523678">http://www.biomedexperts.com/Start/PersonDetailPage.aspx?pid=523678</a>						
<b>Belcher, Angela M</b>	8 Feb 2009	<b>20</b>	<b>26</b>	<b>379</b>	<b>8,508</b>	<b>11.6%</b>
	8 May 2009	<b>21</b>	<b>28</b>	<b>440</b>	<b>9,499</b>	
<a href="http://www.biomedexperts.com/start/PersonDetailPage.aspx?pid=99044">http://www.biomedexperts.com/start/PersonDetailPage.aspx?pid=99044</a>						

Figure 31: Computed social networks based on publications of four MIT professors who researched biotechnology at the ISN (from BiomedExperts.com, 2009).

The number of coauthors is listed, as well as the coauthors' coauthor connections ('friend-of-a-friend' second level or degree connections), as well as the coauthors' coauthor connections ('friend-of-a-friend-of-a-friend' third degree connections). These second and third degrees suggest extended and extendable impact of each author.

The chart also suggests the benefits of renown. Key leaders 'get bigger faster,' with large third-level links to scientific publication co-authors. Social network theory characterizes these extended links as "weak ties," which bridge from the close network

<sup>156</sup>Internet Archive.org, "BiomedExperts.Com."

partners to access different resources and knowledge.<sup>157</sup> Presumably these extended links can be leveraged to do different types of research, learn from interdisciplinary research publications or partners, or exchange student researchers to diversify the skills brought to the shared research.

As shown in the chart, MIT Professor Langer dominates in this domain, with over 400 publications by 2009 partnering with more than 360 co-authors. The length of Langer's career, compared with other ISN researchers, resulted in prolific research, publications, and transition of technologies through established or start-up firms. His success snowballs, attracting emerging talent to research with him, resulting in more papers. Following his example, his co-authors are also prolific, resulting in second-level links with 12,000 co-authors and third-level links with more than a quarter million authors. Such a massive base is hard to increase greatly; Langer's network grew third-level links only eight percent in three months. His third level links may be saturated, with existing researchers tied to each other and therefore to him. In a direct link, Langer and co-author Professor Michael Cima co-founded a company. This double linkage demonstrates Cima's benefit of linking with a highly prolific co-author: creating new opportunities to expand influence into impact by translating knowledge, transitioning technologies, and creating economic activity. The influence of these established authors could eclipse other authors.

Professor Paula Hammond's statistics show a greater percentage of papers with the same co-authors than either Professor Cima or Belcher. This statistic suggests a strategy of focusing articles to describe multiple discoveries from similar research: as

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<sup>157</sup> Granovetter, "The Strength of Weak Ties," May 1973.

described in Chapter 5, Professor Hammond encouraged her co-researchers to publish articles on both new discoveries and the process of creation. At the time, Professor Angela Belcher was an up-and-coming researcher in biotechnology, recognized with a MacArthur 'genius' grant for her innovative approaches, and increasing in publication third-level network links over ten percent in this interval. She and her cohort are growing at a faster rate, although absolute numbers of publications are not yet large. An investment by a research sponsor in this researcher could have the same positive impact as a venture capitalist funding a rising entrepreneurial start-up company. Since Defense research sponsors were pushed to act like venture capitalists in investing in scientific research to accelerate technologies for transition, sponsors would seek these high-leverage investments.

Since their extended social networks are so large, both Langer's and Cima's momentum is harder to influence: each following investment for either research or start-up would be diluted in influence, compared with the prior investments. In contrast, Professor Belcher increased her third-level publication links from 8500 researchers to add 1000 links in three months. Belcher's 'Langer ratio' (comparing her third-degree publication network with Langer's) improved from 28.6:1 in Feb 2009 to 27.7:1 in May 2009, based on her greater rate of increase in this timeframe. To compare, Cima's 'Langer ratio' moved from 7.7 to 5.0, reflecting similar increase in raw numbers of third-degree links as Langer's – as co-authors, they share the expansion of third-degree links. Professor Hammond's moved from 10.6 to 10.7, based on her publications increasing faster than number of co-authors. Since Belcher's 'Langer ratio' showed more change than Hammond's and provides more opportunity to move, investments in her research or

start-up companies could be expected to have a greater relative impact in accelerating innovation. The larger 'Langer ratio' could signal quality of research partnering, or reflect Professor Hammond's openness to partner with less well-linked co-authors. Both research leads offer strategic investors reasons to consider providing resources and sponsorship. For this social analysis, Professor Belcher's network will be the focus; Chapter 5 follows Professor Hammond working with other actor networks, and extending her networks to non-users/non-participants in research, including under-represented minorities.

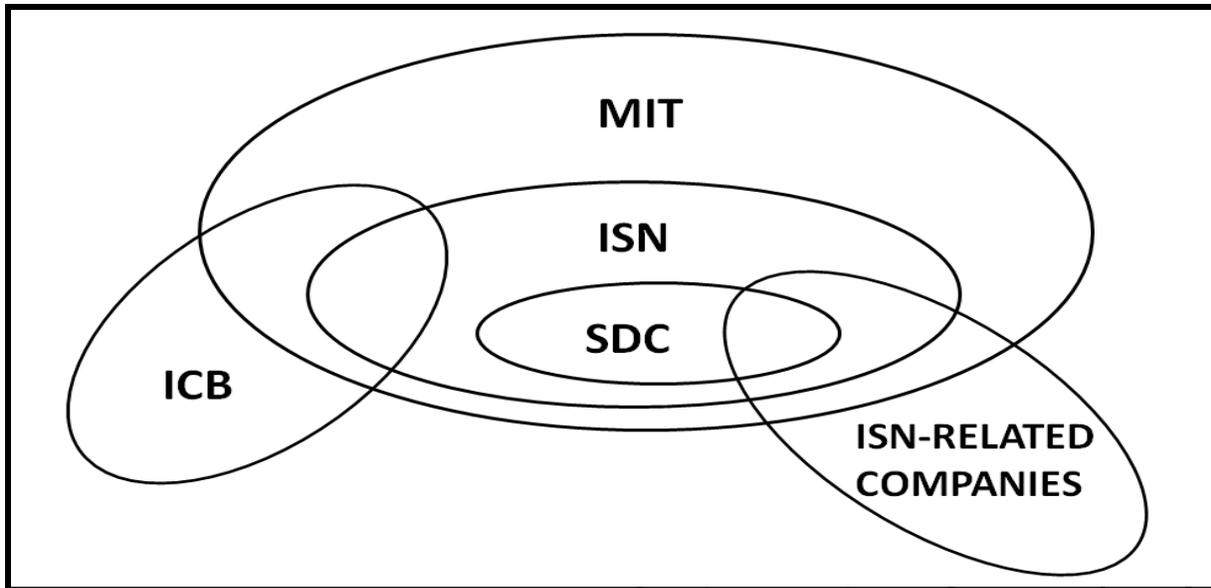
***Step 3: Build out network actor list of entities.***

My starting list of entities was derived from a set of biotechnology publications in top peer-reviewed academic journals, related to Professor Belcher (listed in Table 5). The BioMedExpert.com web site highlighted these publications as related to this researcher. Co-authors for each of the articles provide an inferred social network, since each worked in some capacity with Belcher in basic research that was productive enough to result in a peer-accepted journal article. This co-author list does not yet have correlated metadata, but such additional information can be added later in the analytic process. Similarly, information listed in the co-author list, such as publication name and related geospatial or temporal information, may be explored with follow-on analyses. For this initial analysis, my focus will be on the relative impact of these actors in the context of the ISN research.

In the next step, I augmented the initial list of co-authors by looking for ISN actors and activities. This ***enrichment*** process places listed co-authors into a more detailed context, based on the ISN. In order to focus the quantitative analysis, this process to build out the network, then focus on the core-of-core actors, makes the analysis tractable.

**Table 5. Selected Scientific Publications of Angela Belcher: Inferred Social Network**

10 Apr 2000	<b>Selection of Peptides with Semiconductor Binding Specificity for Directed Nanocrystal Assembly</b> Seung-Wuk Lee, Chuanbin Mao, Christine E. Flynn, Angela M. Belcher	<i>Nature</i> , 8 June 2000, <b>405</b> , 665-668 <a href="https://doi.org/10.1038/35015043">https://doi.org/10.1038/35015043</a>
30 Apr 2002	<b>Emulating biology: Building nanostructures from the bottom up</b> Nadrian C. Seeman and Angela M. Belcher	<i>PNAS</i> , 30 April 2002, <b>99</b> (suppl 2), 6451-6455 <a href="https://doi.org/10.1073/pnas.221458298">https://doi.org/10.1073/pnas.221458298</a>
03 May 2002	<b>Ordering of Quantum Dots Using Genetically Engineered Viruses</b> Seung-Wuk Lee, Chuanbin Mao, Christine E. Flynn, Angela M. Belcher	<i>Science</i> , 3 May 2002, <b>296</b> : 5569, 892-895 DOI: 10.1126/science.1068054
06 Nov 2002	<b>Chiral Smectic C Structures of Virus-Based Films</b> Seung-Wuk Lee, Bryant M. Wood, Angela M. Belcher	<i>Langmuir</i> , 2003, <b>19</b> , 5, 1592-1598 DOI: 10.1021/la026387w
10 Jun 2003	<b>Viral assembly of oriented quantum dot nanowires</b> Chuanbin Mao, Christine E. Flynn, Andrew Hayhurst, Rozamond Sweeney, Jifa Qi, George Georgion, Brent Iverson, Angela M. Belcher	<i>PNAS</i> , 10 June 2003, <b>100</b> :12, 6946-6951 <a href="https://doi.org/10.1073/pnas.0832310100">https://doi.org/10.1073/pnas.0832310100</a>
25 Nov 2003	<b>Viruses as Vehicles for Growth, Organization and Assembly of Materials</b> Christine E. Flynn, Seung-Wuk Lee, Beau R. Peelle, Angela M. Belcher	<i>Acta Materialia</i> , 2003, <b>51</b> :19, 5867-5880 <a href="https://doi.org/10.1016/j.actamat.2003.08.031">https://doi.org/10.1016/j.actamat.2003.08.031</a>
27 Aug 2003	<b>Synthesis and Organization of Nanoscale II-VI Semiconductor Materials Using Evolved Peptides Specificity and Viral Capsid Assembly</b> Christine E. Flynn, Chuanbin Mao, Andrew Hayhurst, J. Williams, George Georgion, Brent Iverson, Angela M. Belcher	<i>J. Mater. Chem.</i> , 2003, <b>13</b> , 2414-2421 DOI: 10.1039/B307593A
20 Oct 2003	<b>Virus-Based Fabrication of Micro- and Nanofibers Using Electrospinning</b> Seung-Wuk Lee, Angela M. Belcher	<i>Nano Letters</i> , 2004, <b>4</b> :3, 387-390 DOI: 10.1021/nl034911t
06 Nov 2002	<b>Chiral Smectic C Structures of Virus-Based Films</b> Seung-Wuk Lee, Bryant M. Wood, Angela M. Belcher	<i>Langmuir</i> , 2003, <b>19</b> :5, 1592-1598 DOI: 10.1021/la026387w
16 Dec 2003	<b>Genetically Driven Assembly of Nanorings Based on the M13 Virus</b> Ki Tae Nam, Beau R. Peelle, Seung-Wuk Lee, Angela M. Belcher	<i>Nano Letters</i> , 2004, <b>4</b> :1, 23-27 DOI: 10.1021/nl0347536
06 Jan 2004	<b>Molecular Orientation of a ZnS-Nanocrystal-Modified M13 Virus on a Silicon Substrate</b> Jingping Ni, Seung-Wuk Lee, John M. White, Angela M. Belcher	<i>Polymer Physics</i> , 15 Feb 2004, <b>42</b> :4, 629-635 <a href="https://doi.org/10.1002/polb.10754">https://doi.org/10.1002/polb.10754</a>
09 Jan 2004	<b>Virus-Based Toolkit for the Directed Synthesis of Magnetic and Semiconducting Nanowires</b> Chuanbin Mao, Daniel J. Solis, Brian D. Reiss, Stephen T. Kottman, Rozamond Y. Sweeney, Andrew Hayhurst, George Georgiou, Brent Iverson, A.M. Belcher	<i>Science</i> , 9 Jan 2004, <b>303</b> :5565, 213-217 DOI: 10.1126/science.1092740
30 Apr 2004	<b>Biological Routes to Metal Alloy Ferromagnetic Nanostructures</b> Brian D. Reiss, Chuanbin Mao, Daniel J. Solis, Katherine S. Ryan, Thomas Thomson, Angela M. Belcher	<i>Nano Letters</i> , 2004, <b>4</b> :6, pp 1127-1132 DOI: 10.1021/nl049825n
16 Jul 2004	<b>Layer-by-Layer Surface Modification and Patterned Electrostatic Deposition of Quantum Dots</b> Saeeda Jaffar, Ki Tae Nam, Ali Khademhosseini, Jia Xing, Robert S. Langer, Angela M. Belcher	<i>Nano Letters</i> , 2004, <b>4</b> :8, 1421-1425 DOI: 10.1021/nl0493287
10 Mar 2005	<b>Bio-inspired Synthesis of Protein-Encapsulated CoPt Nanoparticles</b> Yu Huang, Chung-Yi Chiang, Soo Kwan Lee, Yan Gao, Evelyn L. Hu, James De Yoreo, Angela M. Belcher	<i>Adv. Functional Mat.</i> , Sept 2005, <b>15</b> :9, 1489-1494 <a href="https://doi.org/10.1002/adfm.200400453">https://doi.org/10.1002/adfm.200400453</a>
15 May 2005	<b>Biomaterials functionalization using a novel peptide that selectively binds to a conducting polymer</b> Chuanbin Mao, Christine E. Flynn, Andrew Hayhurst, Rozamond Sweeney, Jifa Qi, George Georgion, Brent Iverson, Angela M. Belcher	<i>Nature Materials</i> , 2005, <b>4</b> , 496-502 <a href="https://doi.org/10.1038/nmat1397">https://doi.org/10.1038/nmat1397</a>
03 Jun 2005	<b>Programmable Assembly of Nanoarchitectures Using Genetically Engineered Viruses</b> Yu Huang, Chung-Yi Chiang, Soo Kwan Lee, Yan Gao, Evelyn L. Hu, James De Yoreo, Angela M. Belcher	<i>Nano Lett.</i> , 2005, <b>5</b> :7, 1429-1434 DOI: 10.1021/nl050795d
19 Sep 2005	<b>Cobalt Ion Mediated Self-Assembly of Genetically Engineered Bacteriophage for Biomimetic Co-Pt Hybrid Material</b> Soo-Kwan Lee, Dong Son Yun, Angela M. Belcher	<i>Biomacromolecules</i> , 2006, <b>7</b> :1, 14-17 DOI: 10.1021/bm050691x
19 Feb 2006	<b>Spontaneous Assembly of Viruses on Multilayered Polymer Surfaces</b> Pil J. Yoo, Ki Tae Nam, Jifa Qi, Soo-Kwan Lee, Juhyun Park, Angela M. Belcher and Paula T. Hammond	<i>Nature Materials</i> , 2006, <b>5</b> , 234-240 <a href="https://doi.org/10.1038/nmat1596">https://doi.org/10.1038/nmat1596</a>
22 Mar 2006	<b>Biomolecular Recognition of Crystal Defects: A Diffuse-Selection Approach</b> A. K. Sinensky and A. M. Belcher	<i>Adv. Materials</i> , Apr 2006, <b>18</b> :8, 991-996 <a href="https://doi.org/10.1002/adma.200502279">https://doi.org/10.1002/adma.200502279</a>
12 May 2006	<b>Virus-Enabled Synthesis and Assembly of Nanowires for Lithium Ion Battery Electrodes</b> Ki Tae Nam, Dong-Wan Kim, Pil J. Yoo, Chung-Yi Chiang, Nonglak Meethong, Paula T. Hammond, Yet-Ming Chiang, Angela M. Belcher	<i>Science</i> , 12 May 2006, <b>312</b> :5775, 885-888 DOI: 10.1126/science.1122716



*Figure 32. Analysis Target: The intersection of networks of biotechnology researchers at MIT, related to the ISN, ISN-related entrepreneurial companies, Soldier Design Competition (SDC), and MIT branch of the Institute for Collaborative Biotechnologies (ICB).*

In order to focus on the network actors of interest in this biotechnology-focused network analysis, I defined the populations, as shown in Figure 1 above. This social network represents a small set of 55 individuals who belong to multiple groups: entrepreneurial business founders who are also biotechnology researchers/MIT professors affiliated with the Army-funded ISN. Co-authors of academic papers who could potentially co-found small biotechnology businesses with these primary investigators are included, as are biotechnology-related small businesses from the ISN. A special interest set of network actors are those MIT student-entrepreneurs who are linked to ISN, biotechnology research, and its prototyping ISN Soldier Design Competition: these entrepreneurial researchers are interested in transitioning lab research to innovative real-world technologies. As part of the competition, these volunteer innovators enrolled partners and teamed to define the problem and proposed solution, consulted with Army

mentors to understand operational constraints, and created relevant working prototypes. During the competition semi-finals and finals, the teams not only demonstrated mechanical objects, but also showed poise and coherence in briefing their work to a panel of senior leaders and an audience of more than 100 viewers. All these experiences enhanced the readiness of these entrepreneurial students to present their research to potential sponsors, and propose small start-up businesses to potential funders and partners. Clearly these individuals participate in many networks, and have varying degrees of impact on each of their several social networks.

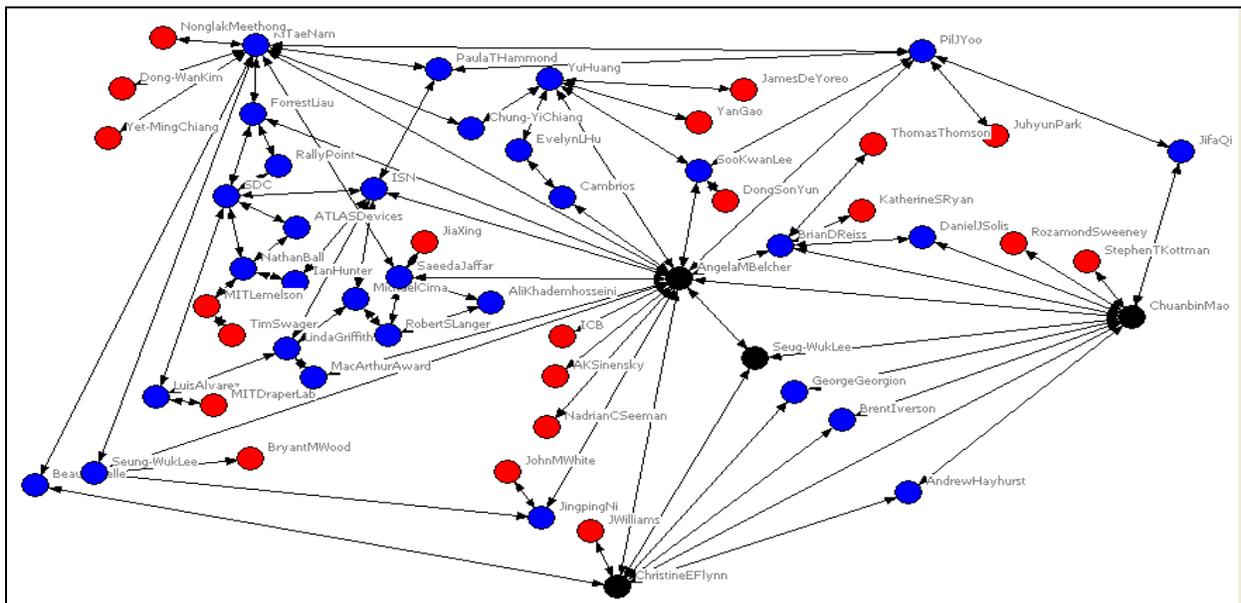


Figure 33. Network graph with cutpoints in Black (suggests hierarchy clustering from Angela Belcher).

In Figure 33, I used UCINET software for initial visualization and statistical analysis of the egos and relationship links in this network.<sup>158</sup> (Based on its improved algorithms and scalability, I also used the SocNetV open source statistical analysis and network visualization software.<sup>159</sup>) This UCINET network diagram graphically displays the

<sup>158</sup> Borgatti, Everett, and Freeman, *UCINET for Windows: Software for Social Network Analysis*.

<sup>159</sup> Kalamaras, *Social Network Visualization (SocNetV)*.

connections between each ego (person, group, or organization) and those connected with it. In this mathematical graph, egos (actors) are shown as nodes, and connections are edges linking egos. Red nodes are connected to single nodes, as a student to a professor might be. Blue nodes indicate triads, with multiple nodes connected to each other. Black nodes indicate the network cutpoints, where boundary spanning actors link substantial parts of the network to the rest of the network. These boundary spanners bridge the different parts of the network, so generate substantial interest as potentially high impact nodes.

The first look at this network diagram shows formal, externally observable, public connections documented in academic publications, funded research, and entrepreneurial business connections. The classic academic connection of one professor as single focal node for several individual students presents several focused links connected to the same node, suggesting an academic hierarchy. Some of these sub-groups may evolve into co-founded businesses. Natural social connections that exist, such as friendship or roommate connections, that are not documented via publicly accessible Internet queries are not included in this analysis, in order to respect concerns about privacy. Similarly, membership networks such as LinkedIn and Facebook may illuminate social connections, but are excluded based on privacy issues. Future researchers may identify means to identify some non-public relationships, but the nature of sharing laboratory spaces and equipment means that some relationships will never be externally observable. Extended private relationships, such as best friend's friendships or non-friendships, affect the social environment, but cannot be discerned from a distance. The dataset is necessarily imperfect, but still provides insight into relationships from a distance of space and time.

#### ***Step 4: Perform data cleansing to generate Edge List.***

The output of the data cleansing step is the edge list, which will be input into the data visualization software. The edge list is composed of the co-authors, augmented by the members of the groups identified above. To cleanse the list, every entity name is validated, and entities which are duplicated names representing two or more people are disambiguated. No occurrences of disambiguation were required for this dataset.

However, entity resolution was required as described above, combining references to the misspelled 'Seug-Wuk Lee' to the correctly spelled 'Seung-Wuk Lee.' Once all references to both spellings were resolved, the number of authors reduced from 56 to 55. This entity resolution also impacted the relative prominence ratings for the statistical measures below, revealing previously under-reported influence and impact by several actors.

After cleansing, disambiguation, and entity resolution, the dataset is curated to match the real-world linkages as expressed in the publications and co-occurrences selected; the dataset shows data validity. The resulting edge list is shown in the table below, to enable other researchers to use the information for reproducibility. The table lists the tuples representing the edge list, showing relationships between the actors (nodes), in the format Source (From), Target (To), and Weight. Weight indicates multiple connections between the same partners.

Table 6. Edge List: Actor-Network Members and Connections shown as Weight.

Source, Target, Weight	
	JingpingNi, Seung-WukLee, 1
AKSinensky, AngelaMBelcher, 1	KiTaeNam, AngelaMBelcher, 3
ATLASDevices, NathanBall, 1	KiTaeNam, BeauRPeelle, 1
BrianDReiss, AngelaMBelcher, 1	KiTaeNam, Chung-YiChiang, 1
BrianDReiss, ChuanbinMao, 1	KiTaeNam, DongSonYun, 1
BrianDReiss, DanielJSolis, 1	KiTaeNam, ForrestLiau, 1
BrianDReiss, KatherineSRyan, 1	KiTaeNam, NonglakMeethong, 1
BrianDReiss, ThomasThomson, 1	KiTaeNam, PaulaTHammond, 1
Cambrios, AngelaMBelcher, 1	KiTaeNam, PilJYoo, 1
Cambrios, EvelynLHu, 1	KiTaeNam, Seung-WukLee, 1
ChristineEFlynn, AndrewHayhurst, 1	KiTaeNam, Yet-MingChiang, 1
ChristineEFlynn, AngelaMBelcher, 2	LuisAlvarez, LindaGriffith, 1
ChristineEFlynn, BeauRPeelle, 1	LuisAlvarez, MITDraperLab, 1
ChristineEFlynn, BrentIverson, 1	MacArthurAward, AngelaMBelcher, 1
ChristineEFlynn, ChuanbinMao, 1	MacArthurAward, LindaGriffith, 1
ChristineEFlynn, GeorgeGeorgion, 1	MichaelCima, LindaGriffith, 1
ChristineEFlynn, JWilliams, 1	MichaelCima, RobertSLanger, 1
ChristineEFlynn, Seung-WukLee, 1	MITLemelson, NathanBall, 1
ChuanbinMao, AndrewHayhurst, 1	MITLemelson, TimothySwager, 1
ChuanbinMao, AndrewHayhurst, 2	NadrianCSeeman, AngelaMBelcher, 1
ChuanbinMao, AngelaMBelcher, 1	NathanBall, IanHunter, 1
ChuanbinMao, AngelaMBelcher, 2	PilJYoo, AngelaMBelcher, 1
ChuanbinMao, BrentIverson, 1	PilJYoo, JifaQi, 1
ChuanbinMao, BrentIverson, 2	PilJYoo, JuhyunPark, 1
ChuanbinMao, BrianDReiss, 1	PilJYoo, KiTaeNam, 1
ChuanbinMao, ChristineEFlynn, 1	PilJYoo, PaulaTHammond, 1
ChuanbinMao, ChristineEFlynn, 1	PilJYoo, SookwanLee, 1
ChuanbinMao, DanielJSolis, 1	RallyPoint, ForrestLiau, 1
ChuanbinMao, GeorgeGeorgion, 3	SaeedaJaffar, AliKhademhosseini, 1
ChuanbinMao, JifaQi, 2	SaeedaJaffar, AngelaMBelcher, 1
ChuanbinMao, RozamondSweeney, 3	SaeedaJaffar, JiaXing, 1
ChuanbinMao, StephenTKottman, 1	SaeedaJaffar, KiTaeNam, 1
ICB, AngelaMBelcher, 1	SaeedaJaffar, RobertSLanger, 1
ISN, AngelaMBelcher, 1	Seung-WukLee, AngelaMBelcher, 2
ISN, ATLASDevices, 1	Seung-WukLee, ChristineEFlynn, 2
ISN, ForrestLiau, 2	Seung-WukLee, ChuanbinMao, 2
ISN, IanHunter, 1	Seung-WukLee, AngelaMBelcher, 3
ISN, LindaGriffith, 1	Seung-WukLee, BryantMWood, 2
ISN, LuisAlvarez, 1	SookwanLee, AngelaMBelcher, 1
ISN, MichaelCima, 1	SookwanLee, Dong-WanKim, 1
ISN, NathanBall, 2	YuHuang, AngelaMBelcher, 2
ISN, PaulaTHammond, 1	YuHuang, Chung-YiChiang, 2
SDC, RallyPoint, 1	YuHuang, EvelynLHu, 2
ISN, SDC, 1	YuHuang, JamesDeYoreo, 2
JingpingNi, AngelaMBelcher, 1	YuHuang, SookwanLee, 2
JingpingNi, JohnMWhite, 1	YuHuang, YanGao, 2

***Step 5: Select analytic tool(s), load data, and iteratively compute statistical measures and visualizations.***

Due to the algorithmic performance of open source SocNetV analytic software, which supported rapid queries and statistical measure generation, the remaining analysis was performed using that toolset. For this 55-actor network graph, a dense network could approach ( $55 \times 54 = 2970$ ) connections. The SocNetV software provides scalability, visualization options, and rapid analysis of key network metrics, which enable the observer to discern relative closeness and importance in the information flow.

SocNetV supports several analytical approaches, both visually and using statistical algorithms. Measures of cohesion in the network, including network shape measures of eccentricity and diameter, do not particularly inform understanding of the impact of actors within this network. The clique dendrogram provides visual assessment of community structure at the subgroup level, showing that many subgroups are similar in size and composition. Prominence measures, including Degree Centrality and PageRank Prestige, help the analyst gain insights into the relative impact of network actors. The Influence Range Closeness Centrality enables understanding of prominence within the context of reachable distances.

As shown in the mathematical graph of the degree centrality in the Belcher network below in Figure 34, many network actors are in the periphery, connected with each other by only one or two connections. These relationships are important, but not reinforced by repeated collaborations, within this network, in this time period, based on the publications reviewed. Although the map is not the full-life reality of these relationships, these tracings of the network can provide insights. In practice, the central actors in this network which

may impact the other actors the most, and translate the science most effectively, are the actors with many linkages. The computer algorithms built into the SocNetV analytic software enable detailed comparisons and quantitative analysis of the roles of the non-periphery actors in this network. I will highlight key centrality measures to identify the most impactful actors in this network in this period.

### Subgroup Structure

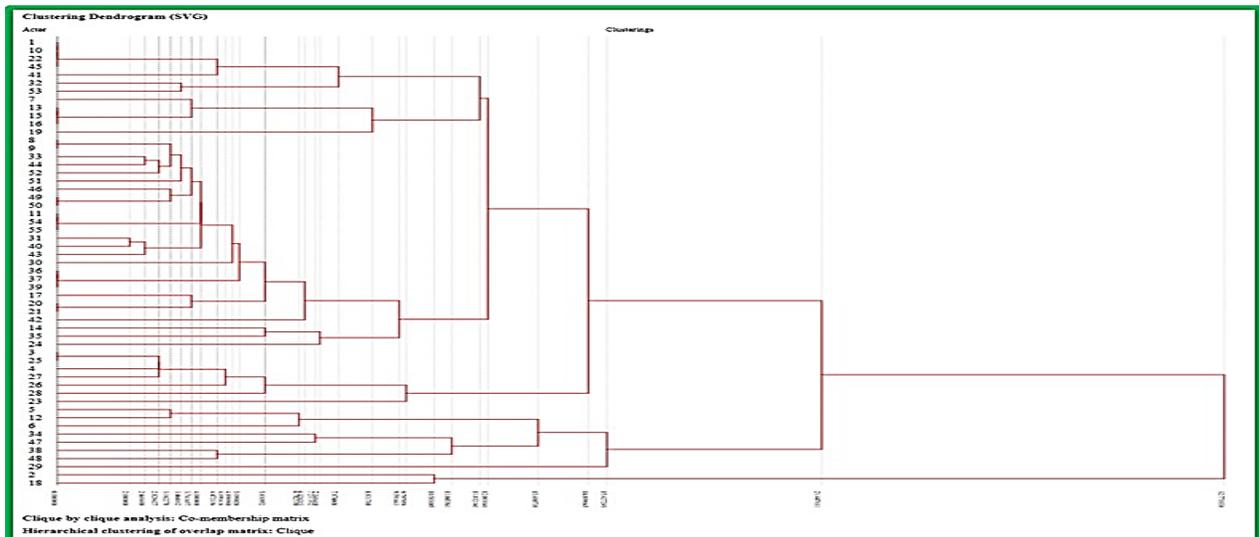


Figure 34. Subgroup Structure: Cliques in the Belcher Social Network (created in SocNetV, 2018).

As an overview of the structure of subgroups, or cliques, the Clique Dendrogram in Figure 35 mathematically graphs how the 55 actors cluster into 30 cliques all directly connected with each other. Cliques represent a maximum complete subgraph of members. For this network, the 55 members organized themselves into 30 cliques ranging from 2 to 16 members, with mean number of members equal to 6.17. Nineteen groups have fewer members than the mean.

The analysis shows that many members belong to small groups of co-authors, with roughly equivalent membership size. These small groups of co-authors make sense,

given the academic structure of professor with one or two students. The subset of articles with more co-authors focused on genetically engineered viruses creating nanomaterials, which Professor Belcher brought with her from University of Texas-Austin to MIT. This structural view of this actor network does not help an analyst identify which members besides Professor Belcher have the most potential impact on the other members of the network. Other measures of centrality and prestige will enable the analyst to determine these subtler differences between actors.

### Degree Centrality

Degree centrality measures how central each node is in terms of number of ties to all other nodes. The top five nodes for degree centrality are listed below, with their measures. The focus of this measure is to assess the number of connections from a node, out to other nodes. (In addition to identifying nodes high in degree centrality, for reproducibility, the SocNetV image captures parameters I used to model this network.)

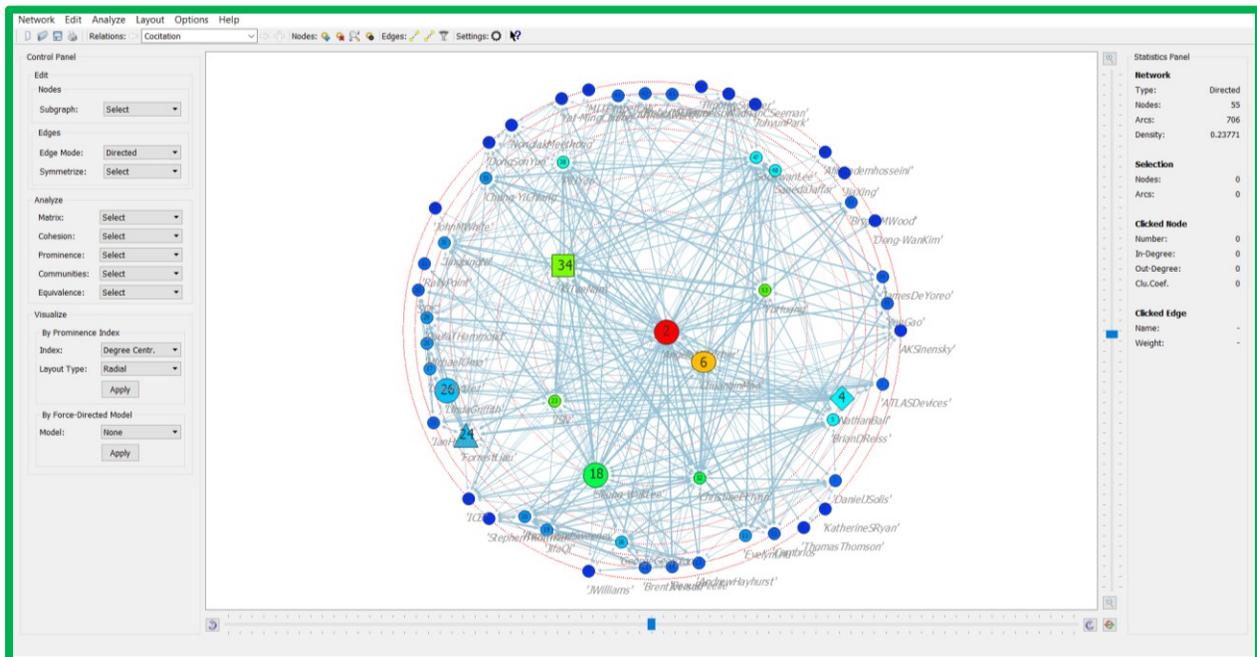


Figure 35. Degree Centrality in the Belcher-centric Social Network.

As shown in Figure 35, created with SocNetV and showing the full visualization analytic console, this Belcher-centric social network is a strongly connected directed network, with 55 nodes, 706 arcs, and a density of 23.77%. The radial layout of the network shows the coloration and placement from the highest-ranking node, Angela Belcher (red dot in center). Mapped out over calibrated rings are the remaining actors, colored from red, to orange, to green, to aqua, to dark blue. Selected nodes are sized up, and will be discussed in the analysis with prominence and prestige analytics below. Edges shown are shorter when nodes are closer to each other, therefore important nodes are centered. This graph positions nodes by their Degree Centrality in the network, a measure that reflects each node's outbound ties with other network actors.

*Table 6. Top Network Nodes for Degree Centrality*

Node	Label	DC	DC'	%DC'	RANK
2	Angela M Belcher	126	0.091	9.052	1/55
18	Seung-Wuk Lee	90	0.065	6.466	2/55
34	Ki Tae Nam	79	0.057	5.675	3/55
12	Christine E Flynn	68	0.049	4.885	4/55
6	Chuanbin Mao	54	0.039	3.879	5/55
24	Forrest Liau	33	0.024	2.371	14/55
4	Nathan Ball	23	0.017	1.652	21/55

**Legend:** For this network, DC score is the sum of ties of outbound edges from each node to all its adjacent nodes. DC range:  $1 \leq DC \leq 126$ . Inverse range:  $0 \leq DC' \leq 1$ .

In SocNetV, the node's degree centrality (DC) measures how many ties a node has with other network nodes. The inverse degree centrality (DC') can be used to understand how active an actor is compared with other network members. The percentage of inverse degree centrality (%DC') measure takes the degree centrality inverse, normalized as a percentage, and enables subtle differences to be differentiated by amplifying faint signals. In this network, Angela Belcher is the most active node, at a

percentage of inverse degree centrality of approximately a third more than Seung-Wuk Lee, and twice that of Ki Tae Nam. This factor highlights Seung-Wuk Lee's work with Professor Belcher at University of Texas-Austin, pioneering the use of viruses to grow nanostructured materials involving quantum dots. This work overlapped with and shares a publication with Ki Tae Nam's involvement as a PhD student in Professor Belcher's MIT research group who using engineered variants of M13 virus to create nano-structured batteries. Ki Tae Nam co-authored several scientific publications, which increased his relative centrality in this network. Both researchers studied chemistry in Seoul, Korea, and did graduate studies in the United States. Post-doctoral fellow Chuanbin Mao worked in Texas on the research using viruses to create nanotechnologies. Christine E. Flynn moved along with the Belcher-led virus engineering research, after earning her PhD from University of Texas-Austin, to post-doctoral fellow at MIT, doing technology transfer through human movement and helping stand up the Belcher Lab.

### *PageRank Prestige*

A second technical measure to understand how the network functions is PageRank Prestige (PRP). Using the Page Rank algorithm used by Google to index web sites, PRP is an importance index that ranks links based on the rank of nodes linking to each link.<sup>160</sup> In effect, this metric shows which nodes are linked to other high-impact nodes (having important friends). In this analysis, the metric applies **not** to web sites, but to **entity** (actor) nodes, to measure the connectedness of nodes with well-connected nodes. Operationally, well-connected nodes could bring more resources if motivated to do so.

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<sup>160</sup> Page et al., "The PageRank Citation Ranking: Bringing Order to the Web."

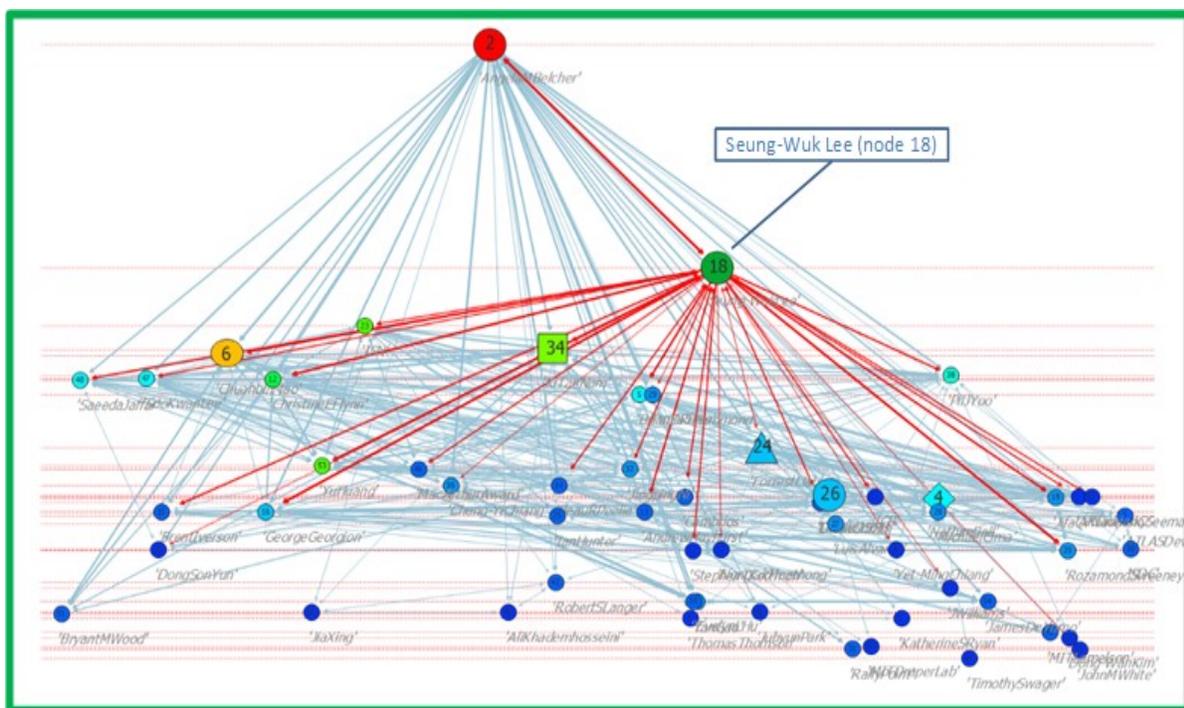


Figure 36. PageRank Prestige graph, highlighting Network Links of Seung-Wuk Lee (Node 18).

The PRP layered graph above shows the rank of each mode, and highlights the network linked with Seung-Wuk Lee (node 18) in red. This node is visually shown as more prominent than all others but Professor Belcher. Specifically, this node is more prominent than Ki Tae Nam (node 34), and Chuanbin Mao (node 6), who worked with Professor Belcher as a post-doctoral fellow after earning his PhD in China. He researched genetically engineered viruses to orient quantum dots into molecular wires, with Seung-Wuk Lee. The team that started this research at University of Texas-Austin transitioned research to the MIT team when Professor Belcher moved her lab.

Faculty members who ranked high in PageRank Prestige (PRP) are Professors Hammond and Griffith. Professor Hammond's co-leadership of ISN research projects with Professor Belcher, along with her prolific research partners, contributed to her higher PageRank Prestige compared with Professor Griffith.

Table 7. Top Network Nodes for PageRank Prestige

Node	Label	PRP	PRP'	%PRP'	RANK
2	Angela M Belcher	0.061	1	100	1/55
18	Seung-Wuk Lee	0.04	0.662	66.159	2/55
23	ISN	0.035	0.573	57.324	3/55
34	Ki Tae Nam	0.033	0.537	53.703	4/55
6	Chuanbin Mao	0.032	0.528	52.822	5/55
29	Paula T Hammond	0.029	0.469	46.876	11/55
24	Forrest Liau	0.024	0.388	38.84	12/55
26	Linda Griffith	0.019	0.317	31.672	18/55
4	Nathan Ball	0.019	0.311	31.07	24/55

**Legend:** Top five nodes for PRP are shown above, with selected other nodes. Maximum PRP is 0.061 (Angela Belcher, node 2). PRP range:  $0.004 \leq PRP \leq 0.061$ , sum = 1, and mean = 0.018. PRP' is the scaled PRP (PRP divided by max PRP).

Graduate students who were involved in the Soldier Design Competition are Forrest Liau (ranked 12 of 55) and Nathan Ball (24 of 55), both above the PRP mean of 0.018. Forrest Liau and Nathan Ball show significantly different numbers of connections. This difference makes sense, since in addition to the Soldier Design Competition Liau joined Belcher's research group for his masters and PhD research. As a result, Liau contributed to more research publications. After completing his master's degree, Ball focused on commercializing his product through his start-up company ATLAS Devices, and worked closely with the ISN to do so. Ball also entered other actor networks, hosting a public television show, *Design Squad*, that featured school-aged engineers prototyping solutions. The ISN node reflects the actors' secondary connections to the ISN, since the ubiquitous first-level connections were eliminated to make this a two-hop network focused on core relations. An example of the secondary connections were the recurring prototype demonstrations by Liau and Ball to subsequent Soldier Design Competition audiences, as alumni teams. (These student entrepreneurs were discussed in chapter 5.)

## Influence Range Closeness Centrality-

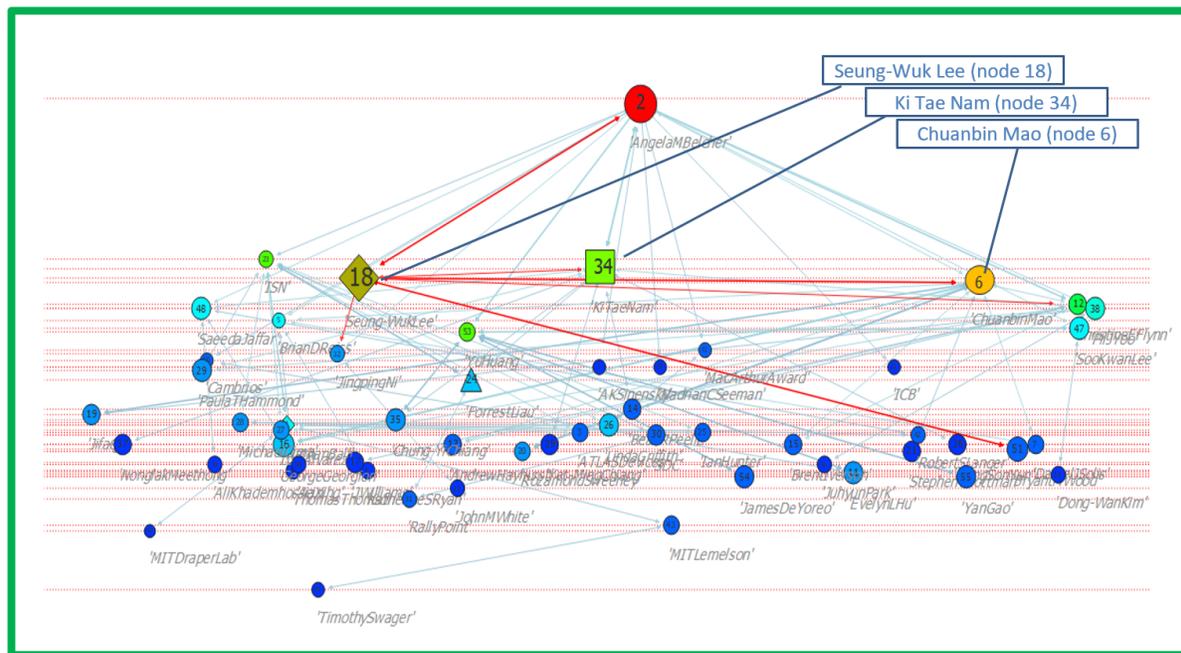


Figure 37. Influence Range Closeness Centrality in the Belcher-centric network.

The Influence Range Closeness Centrality (IRCC) counts outbound distances from each actor node to other reachable nodes, as a ratio of the fraction of reachable nodes to the average distance to those nodes, computed for every node.<sup>161</sup> Thus this measure enables an analyst to assess the reach or influence of each actor.

Table 8. Top Network Nodes for Influence Range Closeness Centrality

Node	Label	IRCC	RANK
2	Angela M Belcher	1.893	1/55
18	Seung-Wuk Lee	1.776	2/55
34	Ki Tae Nam	1.734	3/55
6	Chuanbin Mao	1.654	4/55
24	Forrest Liou	1.502	9/55
4	Nathan Ball	1.183	26/55

**Legend:** For this network, the top four nodes in terms of IRCC index are shown, along with selected others. IRCC range:  $0.547 \leq IRCC \leq 1.893$ ; IRCC mean = 1.168.

<sup>161</sup> Wasserman and Faust, *Social Network Analysis*, 201.

The IRCC factor is strongest for Professor Belcher, as would be expected in this network. This measure enables the analyst to see how closely the next three members fall, with Seung-Wuk Lee followed closely by Ki Tae Nam and Chuanbin Mao. Clearly all three are influential members of the network, linking with many important research partners. The two masters level students are more clearly differentiated by this measure, with Forrest Liao ranked at 9 of 55 actors, while Nathan Ball is ranked close to the mean, at 26 of 55 actors. As a graduate student in the Belcher Lab, Forrest Liao links with more MIT academic actors than Nathan Ball, who links more with external actors through his start-up company, ATLAS Devices. Depending on whether the desired focus is internal/academic, or external/entrepreneurial, a potential sponsor would be able to differentiate which candidate(s) could be worth engaging.

***Step 6: Perform analysis and iterate as needed.***

These quantitative measures from Social Network Analysis illuminate some dynamics working in this strongly connected, fairly balanced network. Even in its early days, key performers can be discerned using the centrality analytics. The Degree Centrality measured the outbound ties of each actor to the other actors, looking outward from each node to other nodes. PageRank Prestige measured the impact of other nodes' relative impact on the node, looking inward from other network nodes and reflecting on the impact of each actor's own network on others. Influence Range Closeness Centrality (IRCC) assessed the reachability of influence for every node, as a proxy factor for impact. Each quantitative measure highlighted a core group of researchers, and enabled the analyst to look more deeply at qualitative accounts to understand the role of each actor in this network. Neither analytic approach alone could uncover the subtle differences

between actors' impact in this early-stage research network; quantitative and qualitative analyses provided different views into the network. These foundational analytics set the stage for more in-depth analysis focused on different aspects of influence by network actors.

Always in data science analyses, the dataset sets the stage for analysis and understanding. By including the Belcher-led research articles from University of Texas-Austin as well as MIT, the transition of key participants such as Christine Flynn from site to site was highlighted. The transition of research from key research participants in Texas, Seung-Wuk Lee and Chuanbin Mao, highlighted the parallel role played by doctoral candidate Ki Tae Nam at MIT. The roughly parallel influence of ISN faculty members Professors Belcher and Griffith foregrounds the ISN requirement for multiple faculty leaders to ensure interdisciplinarity on ISN research projects. The two graduate students who contributed most to the dynamics of this network were Forrest Liao, followed by Nathan Ball. Their multiple reinforcing roles in this dynamic network include research and prototype creation through the Soldier Design Competition. Without these quantitative and qualitative analytic techniques, these nuanced differences in contribution to research and results from the ISN in this period would have been more challenging to identify. The quantitative measures amplify faint signals, and point analysts and potential sponsors to use qualitative techniques to develop more information about the specific details for each actor.

## **Conclusions**

Both the qualitative methods of describing the richly detailed interactions between members of this actor network and the quantitative techniques using data science for

social network analysis provided different insights into how this biotechnology-focused network was connected. Although no tools or techniques can overcome the distance in time and imperfect information, these analytic approaches combine effectively into helping identify strong contributors to Professor Belcher’s research networks. Investors in innovation can use these techniques as foundational to build more detailed assessments.

## Future Research

Assessing the impact of specific scientific publications broadly interests the scientific communities. Journals such as the *Proceedings of the National Academy of Sciences* provide impact metadata for each article, as shown from their website below.

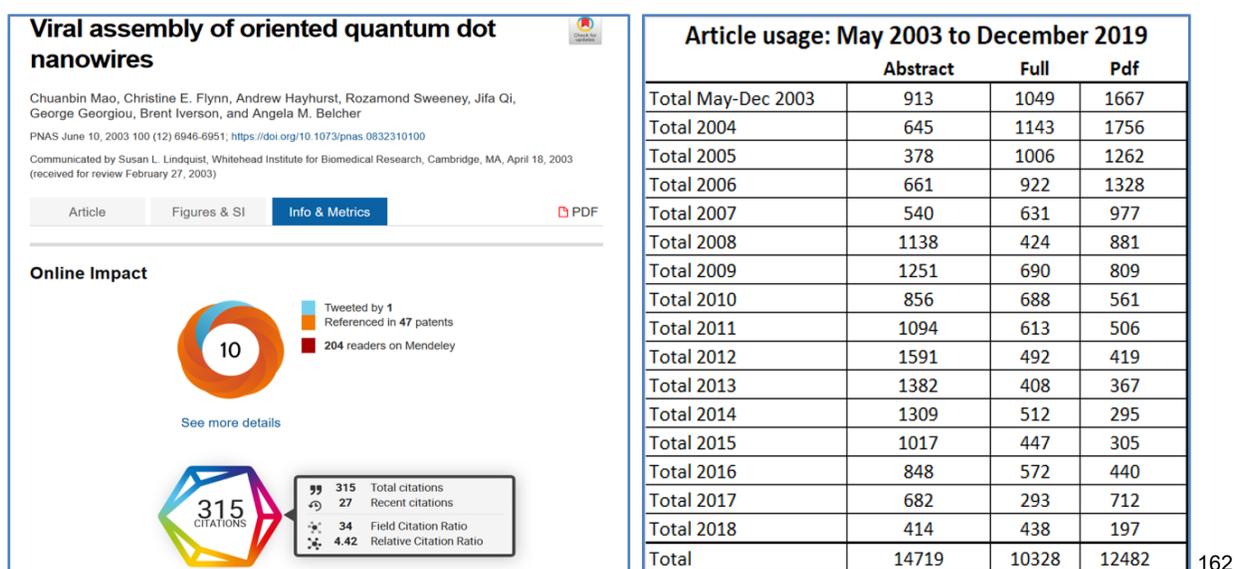


Figure 38. PNAS Impact Assessment Metrics (as of 24 February 2019).

<sup>162</sup> Chuanbin Mao et al., “Viral Assembly of Oriented Quantum Dot Nanowires,” *Proceedings of the National Academy of Sciences* 100, no. 12 (June 10, 2003): 6946–51, <https://doi.org/10.1073/pnas.0832310100>.

Future research to assess the impact of specific actors within a network provides opportunities for practitioners to identify additional investments by research sponsors. Technology-focused research participants could use these techniques to identify potential collaboration partners, or to understand which other research teams show promise in particular areas to inform their competitive analysis of another team or a technology. Would-be industry partners could use these quantitative and qualitative assessments to position potential partnerships or sponsorships to accelerate transition of technologies. Other academic organizations could use these techniques to understand how particular organization configurations proved most ubiquitous in transitioning their own technologies. Would-be research partners could apply these methodologies to identify other institutions to engage in mentor-protégé relationships approaches to accelerate their own research efforts toward transitioning. STS researchers focused on socio-technological innovation can use these quantitative and qualitative methodologies to increase understanding of how teams collaborate and compete in their technology-focused research. The diversity of applications of these analytic techniques create opportunities for technology researcher, creators, analysts, and sponsors.

## **Appendix B.**

# **Quantitative Analytics: Technology Research Team Portfolio Analytics**

### **Overview**

The goal of my analysis is to analyze the ISN's initial portfolio of technology projects and characterize the research projects and the research teams. Quantitative technology research portfolio analysis can be used by participants, research sponsors, potential industry technology transition partners, would-be collaborators or competitors, policy and ethics advisors, and the general public to understand which projects are progressing toward technology for transition. The patterns of activity which are progressing the technology toward transition can be generalized to other research teams, and in some cases to other research domains. These data science methodologies can be applied to a variety of data sets to increase understanding. Analytics can be implemented which are descriptive and diagnostic. In some circumstances, the results may enable analysts to be tentatively predictive, to use insights gained to shape other technology transition-focused research efforts. In the future, these foundational analytics may be useful in a prescriptive mode, to identify potential opportunities to accelerate technology translations, reduce barriers to translations, and/or enroll partners in network to accelerate technologies. I implemented data visualizations and analytics using statistical algorithms. No specific methodology is pre-defined to apply; I created these methodologies broadly informed by combining my knowledge of Defense Acquisition

processes and technology strategy as taught by Professor Rebecca Henderson at MIT.<sup>163</sup>  
I expect to continue to evolve these methodologies.

## **The Six-Step Technology Research Team Portfolio Analytic Process**

### ***Step 1: Define activities and entities of interest.***

My research question is: how did the ISN research projects evolve over time toward the research sponsor's goal of transitioning technologies? I focused on the ISN basic research portfolio established from 2002 to 2007, under the first contract for the emerging institute led by ISN Founding Director, Professor Thomas. Under his leadership, projects were added and ended, based on progress and changes in personnel and sponsor priorities. This analysis is to understand how the different research project teams, which were organized into ISN focus teams, evolved. The goal is to identify entities who may benefit from investment of resources, which can include linking researchers with domain experts to reinforce successful progress, seek to accelerate transitions, and create opportunities to reduce barriers by increasing awareness of the target technology domain and users.

### ***Step 2: Analyze the technology focused research portfolio and select analytical focus.***

The basic research portfolio of the ISN sought to improve human protection, beginning with soldiers as the first users. The research portfolio was organized around seven research focus areas. The seven focus teams were aligned to different challenges confronting dismounted soldiers and emergency first responders. Team 1 researched

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<sup>163</sup> Rebecca Henderson, "Technology Strategy: MIT OpenCourseWare," Spring 2005, <http://hdl.handle.net/1721.1/56570>.

energy-absorbing materials, able to handle ballistic or blast impacts as well as ordinary operations which could harm humans, such as driving vehicles. Team 2 researched mechanically active polymers and devices, scaling solutions from tiny actuators to macro-scale materials that could become rigid on demand to provide splints or armor. Team 3 researched sensors and mechanisms to enhance protection against harmful chemicals and biologic agents, both naturally occurring and man-made hazards. Team 4 researched biomaterials and soldier medical devices, pursuing technologies which could enable automatic medical self-assistance through an integrated future battlesuit or portable medical devices. Team 5 researched processing and characterization, with the intent to create 'nanofoundries' capable of solving initial problems with scaling up production, in order to transfer to industry or defense technologists. Team 6 supported several other teams with computational modeling and simulation of materials and processes. Team 7 integrated participants from the ISN founding industry partners for integration and transition of technology systems. The research focus team leaders created and periodically updated research summaries, which were used to brief potential academic, defense and industry research and transition partners, and inform ISN visitors and the public. The Internet Archive ([archive.org](http://archive.org)) captured digital copies of these research summaries on a periodic basis, providing a corpus of data for the technology research team portfolio analysis.

***Step 3: Capture and cleanse the data.***

Data science analyses focus on the data. For an analysis looking back fifteen years, from an outsider perspective, data gathering often proves challenging, with data sparse, missing, or unavailable due to proprietary controls. In this instance, data exists to

support a robust quantitative analysis. For unknown reasons, the Internet Archive repeatedly captured the research project summaries, saving digital copies of the ISN web site pages.<sup>164</sup> These digital copies may have been spurred by the initial controversy around the ISN contract proposal (discussed in Chapter 3). Whatever the impetus, these web pages were repeatedly captured for this digital library. Changes between one iteration and the next can be compared and analyzed, indicating how the researchers themselves described their projects and progress. The following dates were captured for this analysis: 15 August 2003, 20 April 2004, 9 October 2004, 11 February 2005, and 6 January 2006. For the peak number of 55 projects, observations of the changed web pages were captured, resulting in n=234 data points between 2003 and 2007.

***Step 4: Characterize the data.***

Before performing more complex analyses, the data must be characterized and described in sufficient detail to enable the current and future analysts. Repeatability of the analysis is a crucial component of making the data informative to increase understanding and extend applicability to other similar or contrasting situations. The analysis can be used to inform research investors, whether sponsors or industry technology transition partners, of translation paths used by projects to accelerate technology discovery, development, maturation, and transition. Other potential collaborative or competitive academic partners may use these analytic techniques, to calibrate their expectations about the progress of advancements by scientific domain. Policy makers and ethicists may find these analyses useful, to understand the rate of change and when and how their

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<sup>164</sup> MIT Institute for Soldier Nanotechnologies, "ISN Research Project Summaries," March 2, 2007, <http://web.mit.edu:80/isn/research/researchprojects.html> captured by Internet Archive: <https://web.archive.org/web/20070302140954/http://web.mit.edu:80/isn/research/researchprojects.html>.

complementary analyses may be able to shape technology development, recommend policies, and understand potential use cases.

***Step 5: Implement analytic methodologies, load data, and iteratively compute measures and visualizations.***

In order to characterize the ISN research output from the initial period, first I implemented technology portfolio analysis scoring of each research project along two axes: science to engineering, and product to process. The results for each project were mapped into a Cartesian grid, resulting in each project being assessed into one of four 3x3 quadrants. Selected projects which showed progress toward transitioning that were representative of specific patterns of transition were detailed with subsequent Cartesian grid-based assessment of the project in a subsequent period of time. The quantitative analysis was complemented with a qualitative discussion of the features of the project's progress, including technology transitions as applicable. This approach moves the analysis from descriptive to diagnostic.

***Step 6: Perform analysis and iterate as needed.***

The initial statistically-informed quantitative and qualitative analyses provide a foundation for future analyses. As anomalies are identified, analysts can extend the analysis and perform additional analytics. Anomalies may indicate opportunities to accelerate a technology transition effort. These accelerations can build networks, by adding domain expertise from the users, or by enrolling interdisciplinary scientific or manufacturing expertise from industry partners or defense technologists. Additional user perspectives may help research teams identify extended use cases and communities.

## Performing the Technology Research Team Portfolio Analytic Process

### Step 1: Define the framework for activities and entities of interest.

The ISN research teams described their activities in terms of science and engineering, which move from long-term focus to short-term focus to translate scientific discoveries to technologies for transition. The researchers characterize their work as product or process. Using my research team portfolio analysis framework, I assessed each team as they describe themselves in the project descriptions and placed each research project into 3x3 quadrants in a Cartesian grid focused orientation along the two axes: process to product, and science to engineering. The projects progress within each of the four quadrants (described in Chapter 3), as captured in the ISN project descriptions and reports.

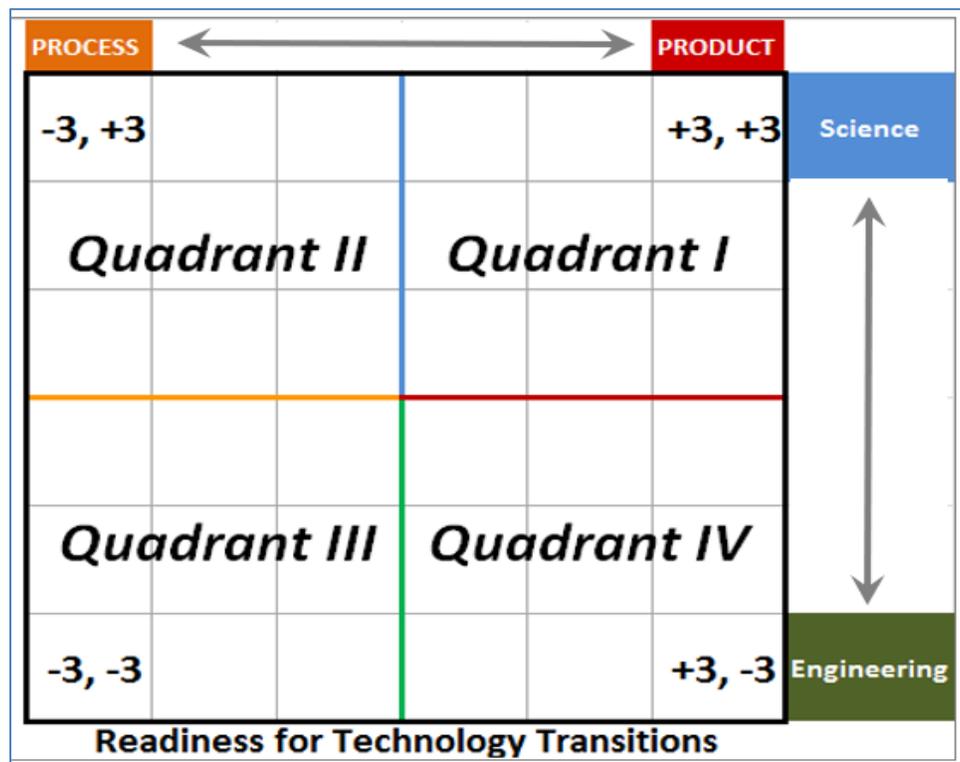


Figure 39. Technology-Focused Research Team Portfolio Analysis (Cartesian Grid)

### ***Step 2: Analyze the research portfolio focused and grounded in research teams.***

The portfolio analysis was grounded in the research teams' own words and graphics that described their research goals and accomplishments. By grounding in the data produced by scientific makers, differences in description emerge from the researchers themselves, avoiding confusion from other perspectives than those from research teams. The emergence of cross-disciplinary and inter-disciplinary approaches and accomplishments can be traced through research project descriptions as changed by the research teams over time. As a result of this analytic focus on the researchers, the analyses to identify patterns of accelerating technology transitions may be extended to other teams, organizations, and research domains.

### ***Step 3: Capture and cleanse the data.***

Gathering the data from the Internet Archive was fundamental. A total of 243 observations of ISN research project summaries were captured. Projects were numbered in typical MIT fashion, with the first digit representing the project team, followed by a period with project number in sequence by research focus team. Anomalies were detected. The seven project teams have gaps in the project number sequence, indicating that projects were eliminated before the first Internet Archive capture: projects 3.7, 5.8, 6.7, and 7.2. Another set of projects were listed with names, but no project summaries were published to the Internet Archive (possibly due to defense security concerns):

- Project 1.8: Nanoscale multilayer film processing--materials studies
- Project 3.4: Viral/peptide bio array sensing systems
- Project 6.1: Hierarchical material assemblies for ballistic and blast protection

Table 9 lists projects, indicating date of Internet Archive capture.

Table 9. Descriptions of ISN Research Projects and Capture Data

Descriptions of ISN Research Projects from Internet Archive on 10/9/2004		15 Aug 2003	20 Apr 2004	9 Oct 2004	11 Feb 2005	6 Jan 2006
<b>Team 1: Energy-absorbing Materials</b>						
1.1	New molecular architectures for ultra-strong energy absorbing polymers	●	●	●	●	●
1.2	Ultra lightweight nanorelief networks, self assembled microtrusses and photopatterned nanocomposites	●	●	●	●	●
1.3	Mechanics of active materials	●	●	●	●	■
1.4	Synthesis and resin-spinning of artificial silk-like polymers	●	●	●	●	●
1.5	Single-shot time-resolved spectroscopy of ballistic impact events	●	●	●	●	●
1.6	Multiscale design and evaluation of biological and synthetic nanostructured materials for ballistic and blast protection	●	●	●	●	●
1.7	Dynamic FTIR (Fourier Transform Infrared Spectroscopy)	●	●	●	●	■
1.8	Nanoscale multilayer film processing--materials studies	●	○	●	●	■
1.9	Hierarchical material assemblies for ballistic and blast protection	●	●	●	●	■
1.1	Investigation of deformation and failure mechanisms in high performance fabrics	●	●	●	●	■
<b>Team 2: Mechanically Active Materials and Devices</b>						
2.1	Nanostructured polymer actuators	●	●	●	●	●
2.2	Optimization of conducting polymer actuators	●	●	●	●	●
2.3	Liquid crystalline thermoplastic elastomers for actuator and electromechanical applications	●	●	●	●	●
2.4	Chemically-switchable magnetic materials for actuators	●	●	●	●	●
2.5	Model-based control of mechanically active materials	●	●	●	●	■
<b>Team 3: Sensors and Chemical/Biological Protection</b>						
3.1	Microbicidal, antiviral, and antispore fabrics and other materials	●	●	●	●	●
3.2	IR (Infrared) detection systems for optical sensing	●	●	●	●	●
3.3	Active/passive cylindrical photonic crystal systems	●	●	●	●	■
3.4	Viral/peptide bio array sensing systems	●	○	●	●	●
3.5	Dendrimer/nanoparticle assemblies as chemical toxin deactivation coatings	●	●	●	●	●
3.6	High sensitivity sensors based on conducting and semiconducting organic molecules and polymers	●	●	●	●	●
(No 3.7 listed)						
3.8	Block copolymer based conjugated polymer sensing system	●	●	●	●	●
3.9	]High performance cell-based sensors for unknown infectious agents	●	●	●	●	●
3.1	Photonic bandgap fibers with discrete rotational symmetries	■	●	■	■	■
3.11	Engineering cellular nano-dynamics in the development of a physiomic LiverChip sensor for infectious viruses	■	●	■	■	■
3.12	Computation, prediction and verification of photonic properties of polymer based nanocomposites	●	●	●	●	●
3.13	Multilayer thin films for photonic bandgap materials	■	■	●	●	■
3.14	Flourescent sensing technologies for sensitive and selective detection of chemical warfare agents	■	■	●	●	■
3.15	Transitioning of ultra-high sensitivity sensors based on electronic polymers nanotechnology for chemical sensing for dismounted soldier	■	■	●	●	■
3.16	Transitioning of nanotechnology-based visible and IR detection systems	■	■	●	●	■
3.17	Nanostructured surfaces for live cell pathogen sensing	■	●	●	●	●

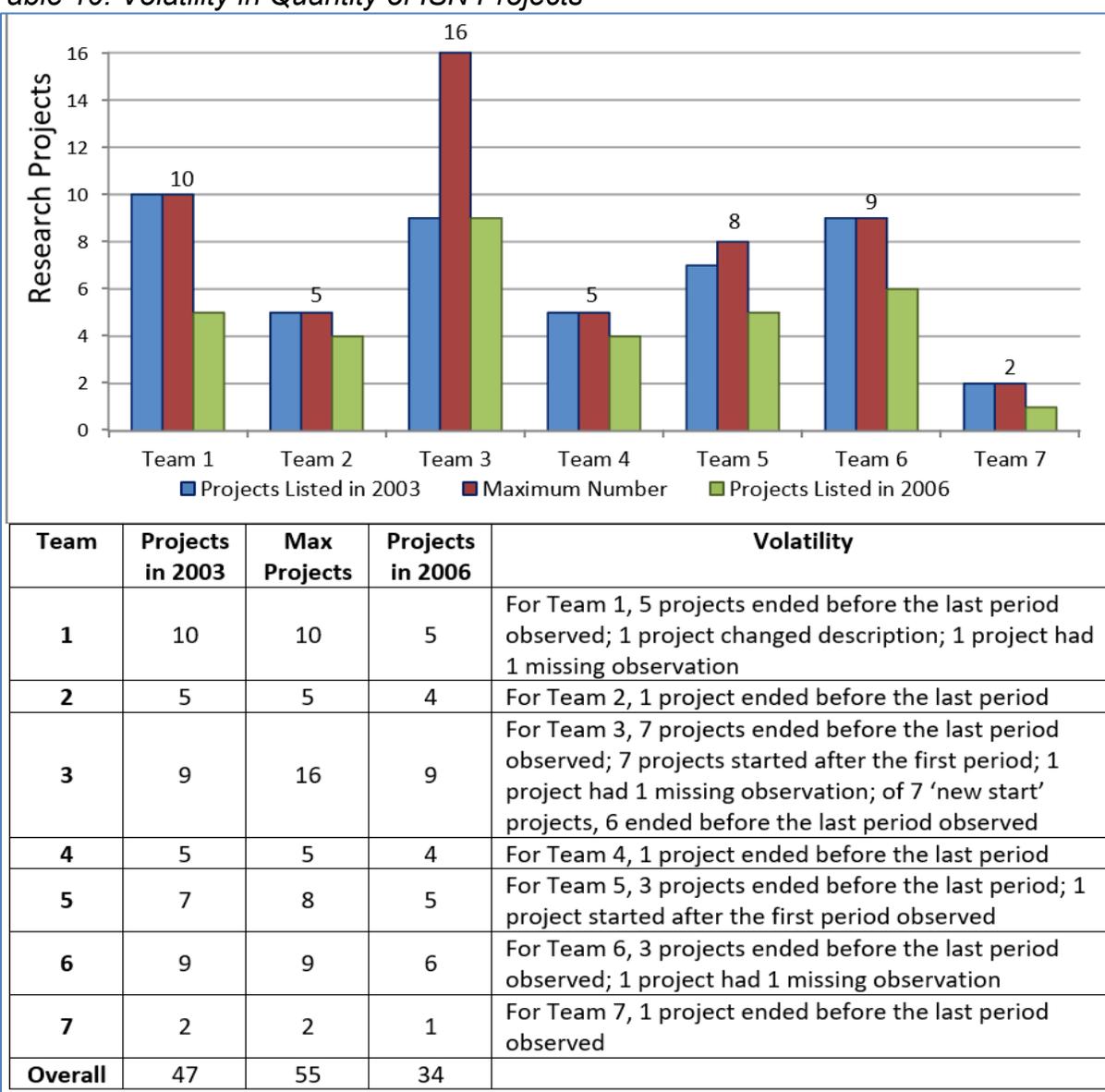
(Table 9 Continued)

Descriptions of ISN Research Projects from Internet Archive on 10/9/2004		15 Aug 2003	20 Apr 2004	9 Oct 2004	11 Feb 2005	6 Jan 2006
<b>Team 4: Biomaterials and Nanodevices for Soldier Medical Technology</b>						
4.1	Switchable surfaces	●	●	●	●	●
4.2	Non-invasive diagnostics and delivery of injury intervention agents	●	●	●	●	●
4.3	Semi-active variable-impedance materials: biomechanical design and control	●	●	●	●	●
4.4	Nanostructured biomedical fiber constructs	●	●	●	●	●
4.5	Field responsive fluids for load transfer in splints and other medical devices	●	●	●	●	■
<b>Team 5: Processing and Characterization/The Nanofoundries</b>						
5.1	Processing of fibers and fibrous materials	●	●	●	●	●
5.2	Nanoscale multilayer film processing	●	●	●	●	●
5.3	Field-responsive fluids in microchannels and microfluidic devices	●	●	●	●	■
5.4	Chemical vapor deposition polymers	●	●	●	●	●
5.5	Three-dimensional integration of microfluidic devices and fiber networks	●	●	●	●	■
5.6	Low pressure material deposition by misted solution transport	●	●	●	●	■
5.7	Nanostructured origami: 3D nanopatterning via folding of 2D membranes	●	●	●	●	●
	(No 5.8 listed)	■				
5.9	Hybrid hard/ductile nanocomposites	■		●	●	●
<b>Team 6: Modeling and Simulation of Materials and Processes</b>						
6.1	Hierarchical material assemblies for ballistic and blast protection	●	○	●	●	■
6.2	Design/ tuning nanoparticles for mechanical, electronic and chemical properties	●	●	●	●	●
6.3	Novel electro-osmotic microfluidic devices	●	●	●	●	●
6.4	Electronic-structure modeling of polymer actuators	●	●	●	●	●
6.5	Dissipative particle dynamics studies of nanocomposite rheology	●	●	●	●	■
6.6	Multiscale modeling of nanocomposites	●	●	●	●	■
	(No 6.7 listed)	■				
6.8	Modeling and simulation of deformation and failure behavior in woven fabrics	●	●	●	●	●
6.9	Simulation of behind-armor effects of ballistic threats	●	●	●	●	●
6.10	High performance simulation of blast-soldier interactions	●	●	●	●	●
<b>Team 7: Integration and Transitioning of Technology Systems</b>						
7.1	Virtual human project: Continuum model to determine physiological responses	●	●	●	●	■
	(No 7.2 listed)	■				
7.3	Battlesuit systems architectures for optimal use of nanotechnologies	●	●	●	●	●
<b>55</b>	Total Projects / Observations by Date (n=234)	<b>47</b>	<b>47</b>	<b>53</b>	<b>53</b>	<b>34</b>
Legend: ● = Observation on Internet Archive on listed date; ○ = Missing Observation in Series						
Data Source: ISN Project Pages from <a href="http://web.mit.edu:80/isn/research/researchprojects.html">http://web.mit.edu:80/isn/research/researchprojects.html</a> , captured on Dates Shown Above; captured on Internet Archive: <a href="https://web.archive.org/web/20070302140954/http://web.mit.edu:80/isn/research/researchprojects.html">https://web.archive.org/web/20070302140954/http://web.mit.edu:80/isn/research/researchprojects.html</a>						

#### Step 4: Characterize the data.

A set of projects started after the initial period, and others ended early. These changes contribute to volatility in the ISN research portfolio. Table 2 below describes the additions and endings by each research focus team. Reasons for early endings varied. Two Team 6 projects ended when the lead researcher, Dr. Beers left MIT to become a consultant. Other projects ended when student researchers graduated.

Table 10. Volatility in Quantity of ISN Projects



**Step 5: Perform analysis iteratively to detect and explore anomalies.**

One anomaly that impacted a set of projects caused descriptions to be changed for one observation, captured by the Internet Archive in April 2004, but then reverted back to the original descriptions. These changes can be categorized: specified application (6 projects), generalized application (2 projects), or specified study (7 projects).

**Table 11. Project Descriptions Changed Temporarily by April 2004**

Project	Description in August 2003 / Restored after October 2004	Description Changed in April 2004	Change Category
1.4	Synthesis and resin-spinning of artificial silk-like polymers	New mechanically enhanced, functional nanostructured polyurethane systems for soldier applications	SA
1.7	Dynamic FTIR ( <i>Fourier-transform infrared spectroscopy</i> )	Dynamic FTIR microstructural evaluation of structured materials and fabrics for ballistic and blast protection	SS
2.2	Optimization of conducting polymer actuators	Optimization of conducting polymer actuators: materials, design, and devices	SS
3.8	Block copolymer based conjugated polymer sensing system	Self-organizing anisotropic nanoelectronic structures	SA
3.9	High performance cell-based sensors for unknown infectious agents	High performance sensing technologies for unknown infectious agents	GA
5.2	Nanoscale multilayer film processing	Nano-scale multilayer films processing, properties and morphology	SS
5.3	Field-responsive fluids in microchannels and microfluidic devices	Field-responsive fluids and microstructures for adaptive energy absorption applications	SA
5.4	Chemical vapor deposition polymers	Chemical vapor deposition polymers for Soldier Suit interconnection	SA
6.2	Design/ tuning nanoparticles for mechanical, electronic and chemical properties	Understanding, designing, and tuning the response of nanomaterials and nanodevices to target mechanical, electrical and chemical properties	SS
6.3	Novel electro-osmotic microfluidic devices	Induced-charge electro-osmotic microfluidic devices	SA
6.4	Electronic-structure modeling of polymer actuators	First-principles description of structural, mechanical, and electronic properties of conducting polymer actuators	SS
6.5	Dissipative particle dynamics studies of nanocomposite rheology	Dissipative particle dynamics studies of nanocomposite morphology	SS
6.6	Multiscale modeling of nanocomposites	Multiscale modeling of nanocomposite mechanical properties	SS
6.8	Modeling and simulation of deformation and failure behavior in woven fabrics	Modeling and simulation of deformation and failure behavior in high performance fabrics	SA
7.3	Battlesuit systems architectures for optimal use of nanotechnologies	Systems architectures for optimal use of nanotechnologies	GA
<i>Legend: SA = Specified Application; GA = Generalized Application; SS = Specified Study</i>			

Why might the descriptions have been changed in this interval? Two key events involving outside parties occurred in the window of the change. The first event was the second ISN Industry Day in March 2004, seeking to recruit new industry partners in different categories:

Zyvex Corporation joined as a Small Business Industrial Member, and Mine Safety Appliances Company joined as an Interested Industrial Participant.... to transition promising results of ISN basic research into practical products that can be produced affordably in large quantities for Soldiers.<sup>165</sup>

Industry partners were critical to scaling up manufacturing and production, as well as translating designs and prototypes into market-ready products. The potential industry partners would seek both more specifically described applications, to target a particular market segment or user; as well as more generally described applications, to respond to previously untargeted user groups.

In addition, in September 2003 the ISN held a major research enrollment and networking event with more than 100 Army, Defense, and Industry S&T partners:

...ISN hosted a four-day research review meeting where each of its 42 research projects was presented and reviewed by a panel of Army and other government subject matter experts (Capability Area Review Teams, or CARTs). About 140 people from the Army, DoD, and ISN industry partner companies attended....<sup>166</sup>

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<sup>165</sup> MIT Institute for Soldier Nanotechnologies, "ISN Adds New Industry Partners," *ISN News*, September 2004.

<sup>166</sup> Thomas, "MIT Reports to the President 2003–2004: Institute for Soldier Nanotechnologies."

The CART represented a new approach for Army research sponsors to engage Army S&T, creating networking opportunities for potential partnerships to transition the basic research to applied research, as well as enrolling representatives from different Army user communities. Army Acquisition personnel attended, to prepare to acquire the technologies emerging from the ISN, student teams, start-up businesses, and industry partners.

**Step 6: Perform analysis and iterate as needed.**

The technology research team portfolio analytic process begins by assessing every project and encoding start and end positions, based on research summaries, according to the Cartesian grid (-3 to +3) as shown below. The goal is to understand where the projects begin, scoring each project based on described intent and projected accomplishments. This analyst compared the progress described in the ISN research project summaries, and scores the research project in a subsequent time period. For this analysis, I sought to identify a set of ISN projects demonstrating separate patterns of team behavior to progress toward technology transitions.

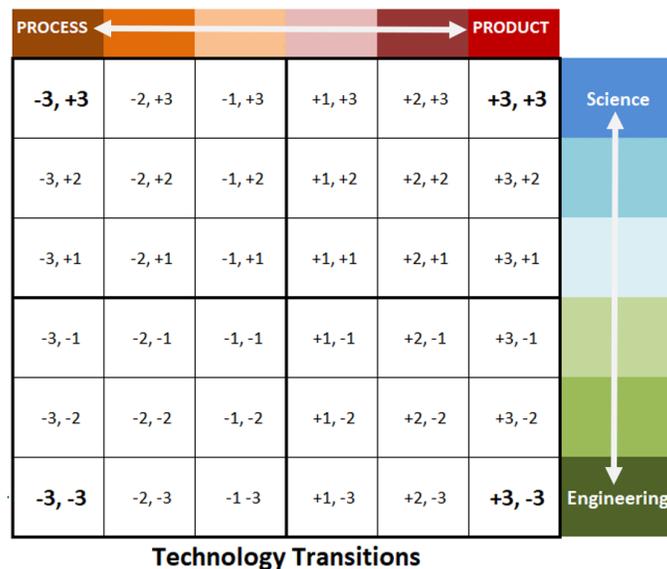
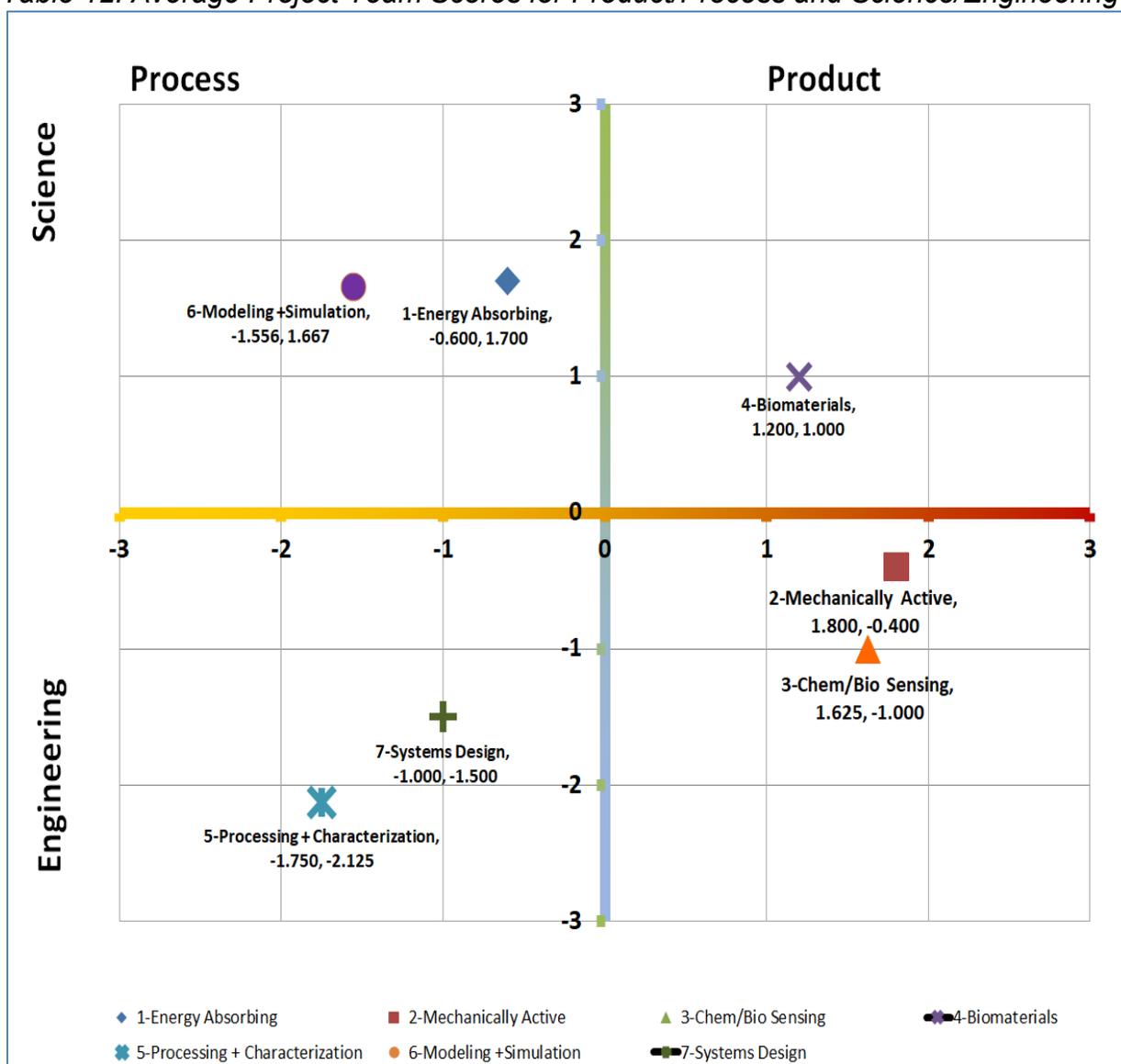


Figure 40. Cartesian Grid for Scoring Technology Research Projects

Table 12. Average Project Team Scores for Product/Process and Science/Engineering



Team	/Initial Scores	# Projects	Process- Product	Science- Engineering	Std Dev P/P	Std Dev S/E
1: Energy-absorbing Materials		10	-0.600	1.700	2.366	1.252
2: Mechanically Active Materials and Devices		5	1.800	-0.400	1.789	1.817
3: Sensors and Chemical/Biological Protection		16	1.625	-1.000	1.025	1.461
4: Biomaterials / Nanodevices for Soldier Medical Technology		5	1.200	1.000	1.924	2.739
5: Processing and Characterization/The Nanofoundries		8	-1.750	-2.125	1.389	0.835
6: Modeling and Simulation of Materials and Processes		9	-1.556	1.667	1.590	1.581
7: Systems Design, Hardening, and Integration		2	-1.000	-1.500	2.828	0.707
Overall 7 Teams	/ Average	55	0.127	-0.027	1.414	1.556

As shown in Table 4, the average team positioning falls in all four quadrants. In Quadrant I, focused most on science and products, falls the preponderance of Team 4 biomedical projects. In Quadrant II, where researchers focus most on science and processes, both Team 1 energy-absorbing materials and Team 6 computational modeling projects provide both internal team support and cross-team support. Continuing counterclockwise to Quadrant III, projects that focus on process and engineering include Team 5 processing and characterization – the Nanofoundries scaling up manufacturing – and Team 7, overall systems integration projects. Finally, in Quadrant IV, projects focused on engineering and products emerged from Teams 3, with specific target-focused chemical and biological sensors, and Team 2, mechanically active materials and devices.

As shown in Table 5, I scored each ISN Project for Process-Product and Science-Engineering focus based on the project summary descriptions. Each of the projects is individually rated, and then average scores for each team are computed. Statistics computed for each team also include the standard deviation for each axis, so that each individual project can be analyzed in the context of its variation from the group mean and variability of the scores of other projects in each project focus team. A small standard deviation would indicate that most projects are similar to each other in terms of the positioning factor being scored. A large standard deviation would indicate greater diversity in positioning along the factor axis being evaluated. These foundational statistical measures support deeper follow-on analyses. By comparing ratings from different time periods, insights can be gained about how the individual teams progress toward technology transition, as well as providing larger strategic insights.

Table 13. ISN Projects Scored for Process-Product and Science-Engineering Focus

Project Descriptions		Scores	Scoring			
			Process-Product	Science-Engineering	Std Dev P/P	Std Dev S/E
Team 1	1.1	New molecular architectures for ultra-strong energy absorbing polymers	2	3		
	1.2	Ultra lightweight nanorelief networks, self assembled microtrusses and photopatterned nanocomposites	2	3		
	1.3	Mechanics of active materials	-2	3		
	1.4	Synthesis and resin-spinning of artificial silk-like polymers	3	2		
	1.5	Single-shot time-resolved spectroscopy of ballistic impact events	-3	-1		
	1.6	Multiscale design and evaluation of biological and synthetic nanostructured materials for ballistic and blast protection	-2	1		
	1.7	Dynamic FTIR	-3	1		
	1.8	Nanoscale multilayer film processing--materials studies	-3	2		
	1.9	Hierarchical material assemblies for ballistic and blast protection	1	2		
	1.10	Investigation of deformation and failure mechanisms in high performance fabrics	-1	1		
<b>Team 1 Energy-absorbing Materials / Average</b>		<b>-0.600</b>	<b>1.700</b>	<b>2.366</b>	<b>1.252</b>	
Team 2	2.1	Nanostructured polymer actuators	3	2		
	2.2	Optimization of conducting polymer actuators	3	1		
	2.3	Liquid crystalline thermoplastic elastomers for actuator and electromechanical applications	1	-1		
	2.4	Chemically-switchable magnetic materials for actuators	3	-1		
	2.5	Model-based control of mechanically active materials	-1	-2		
<b>Team 2 Mechanically Active Materials and Devices / Average</b>		<b>1.800</b>	<b>-0.400</b>	<b>1.789</b>	<b>1.817</b>	
Team 3	3.1	Microbicidal, antiviral, and antispore fabrics and other materials	1	-2		
	3.2	IR detection systems for optical sensing	2	-1		
	3.3	Active/passive cylindrical photonic crystal systems	2	1		
	3.4	Viral/peptide bio array sensing systems	3	1		
	3.5	Dendrimer/nanoparticle assemblies as chemical toxin deactivation coatings	3	-1		
	3.6	High sensitivity sensors based on conducting & semiconducting organic molecules and polymers	2	-2		
	3.8	Block copolymer based conjugated polymer sensing system	1	-2		
	3.9	High performance cell-based sensors for unknown infectious agents	1	-1		
	3.10	Photonic bandgap fibers with discrete rotational symmetries	2	-2		
	3.11	Engineering cellular nano-dynamics in development of physiomic LiverChip sensor for infectious viruses	1	-2		
	3.12	Computation, prediction & verification of photonic properties of polymer based nanocomposites	-1	-1		
	3.13	Multilayer thin films for photonic bandgap materials	1	1		
	3.14	Flourescent sensing technologies for sensitive and selective detection of chemical warfare agents	2	-2		
	3.15	Transitioning of ultra-high sensitivity sensors based on electronic polymers nanotechnology for chemical sensing for the dismounted soldier	2	-1		
3.16	Transitioning of nanotechnology-based visible and IR detection systems	3	-3			
3.17	Nanostructured surfaces for live cell pathogen sensing	1	2			
<b>Team 3 Sensors &amp; Chemical/Biological Protection / Average</b>		<b>1.625</b>	<b>-1.000</b>	<b>1.025</b>	<b>1.461</b>	
Team 4	4.1	Switchable surfaces	3	3		
	4.2	Non-invasive diagnostics and delivery of injury intervention agents	2	3		
	4.3	Semi-active variable-impedance materials: biomechanical design and control	-2	3		
	4.4	Nanostructured biomedical fiber constructs	1	-2		
	4.5	Field responsive fluids for load transfer in splints and other medical devices	2	-2		
<b>Team 4 Biomaterials &amp; Nanodevices for Soldier Medical Technology / Average</b>		<b>1.200</b>	<b>1.000</b>	<b>1.924</b>	<b>2.739</b>	
Team 5	5.1	Processing of fibers and fibrous materials	-1	-2		
	5.2	Nanoscale multilayer film processing	-2	-3		
	5.3	Field-responsive fluids in microchannels and microfluidic devices	1	-3		
	5.4	Chemical vapor deposition polymers	-1	-3		
	5.5	Three-dimensional integration of microfluidic devices and fiber networks	-3	-2		
	5.6	Low pressure material deposition by misted solution transport	-3	-1		
	5.7	Nanostructured origami: 3D nanopatterning via folding of 2D membranes	-2	-1		
	5.9	Hybrid hard/ductile nanocomposites	-3	-2		
<b>Team 5 Processing and Characterization/ Nanofoundries / Average</b>		<b>-1.750</b>	<b>-2.125</b>	<b>1.389</b>	<b>0.835</b>	
Team 6	6.1	Hierarchical material assemblies for ballistic and blast protection	1	-2		
	6.2	Design/ tuning nanoparticles for mechanical, electronic and chemical properties	-1	1		
	6.3	Novel electro-osmotic microfluidic devices	1	1		
	6.4	Electronic-structure modeling of polymer actuators	-2	2		
	6.5	Dissipative particle dynamics studies of nanocomposite rheology	-3	3		
	6.6	Multiscale modeling of nanocomposites	-3	2		
	6.8	Modeling and simulation of deformation and failure behavior in woven fabrics	-2	2		
	6.9	Simulation of behind-armor effects of ballistic threats	-2	3		
	6.10	High performance simulation of blast-soldier interactions	-3	3		
	<b>Team 6 Modeling and Simulation of Materials and Processes / Average</b>		<b>-1.556</b>	<b>1.667</b>		
Team 7	7.1	Virtual human project: Continuum model to determine physiological responses	-3	-1		
	7.3	Battlesuit systems architectures for optimal use of nanotechnologies	1	-2		
<b>Team 7 Systems Design, Hardening, and Integration / Average</b>		<b>-1.000</b>	<b>-1.500</b>	<b>2.828</b>	<b>0.707</b>	
<b>Overall 7 Teams</b>			<b>0.127</b>	<b>-0.027</b>	<b>1.414</b>	<b>1.556</b>

Legend: Projects are scored twice along 2 axes: Project↔Process and Science↔Engineering. Standard Deviations in scores are assessed at the team level.

## ISN Project Patterns of Enrollment

Overall, each of the seven teams positioned their 55 total projects in a roughly balanced portfolio which fills spaces between science and engineering focus, and process and product implementation. The additions and endings of different projects required the ISN leadership to work to keep the portfolio balanced. All teams demonstrated collaborated in an interdisciplinary manner with other MIT, industry, and Army S&T partners. Patterns of enrollment were shown by a set of projects, to be described below and in more detail in Chapter 3.

### Rapid Technology Transition in FIDO Explosives Detector

Professor Timothy Swager led the research and partnered with ISN small business partner, Nomadics, to accelerate the transition of the FIDO explosives detector. Swager's team developed a novel material, amplifying fluorescent polymers (AFP), which reacted to hazardous substances in vapor. Product science translated to process science, then to product engineering. Nomadics engineered a device to contain AFP, tested with users, and scaled up manufacturing.

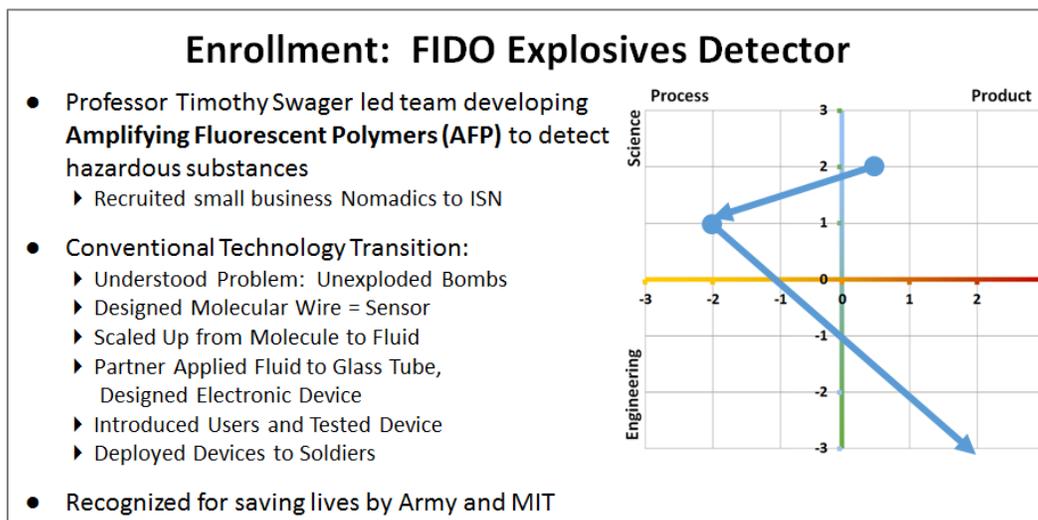


Figure 41. Enrollment: FIDO Explosives Detector

Nomadics 'black boxed' the scientific components in the glass tube within the handheld explosives detector. After Army users tested the device in operationally-relevant proving ground in Arizona, Army acquisition specialists at the Rapid Equipping Force procured hundreds of FIDO devices and deployed them with training to users in Iraq, then Afghanistan. Despite the unprecedented speed in moving from lab to saving soldiers' and civilians' lives, FIDO represents a conventional technology transition. The research team understood the problem: detecting unexploded bombs. They decomposed the problem into its component parts. They identified the most frequently occurring explosive in the zones of combat where soldiers currently operated. They designed the AFP to serve as a molecular wire, a sensor, tuned exquisitely to detect particles of that frequently occurring explosive. They scaled up the design and partnered with business to apply the fluid to glass tubes, inserted into an engineered device. Devices were shared with partner organizations, including host nation police who were defending against explosives.

### **Medical Enrollment**

Partnering on medical projects represents a second pattern of enrollment, demonstrated by Professor Langer's two biomedical projects on team 4. Project 4.1 focused on switchable surfaces was based on a quadrant I novel scientific discovery project. The concept was a molecular structure that was hydrophilic, with loose molecules that allowed water to pass through; then changed to hydrophobic and rigid when the molecule strands bent over when activated by chemistry or electricity. The application could become an on-demand bandage in a soldier battlesuit, that automatically responded to liquid such as blood. After networking with Army S&T and medical partners,

Professor Langer recognized that the key barrier was scaling up manufacturing, so shifted the project to focus to process engineering.

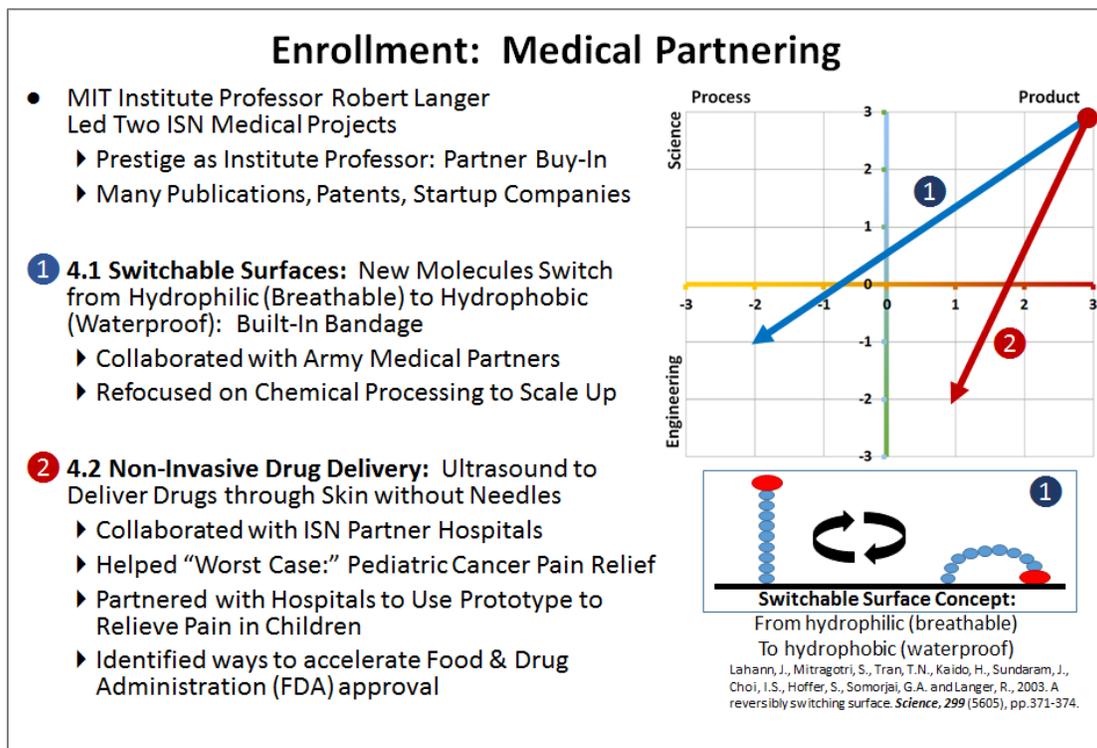


Figure 42. Enrollment: Medical Partnering with Projects led by MIT Professor Langer

Langer’s project 4.2 on noninvasive drug delivery followed a similar pattern, from product science, to process engineering. After networking with ISN industry partner hospitals, a target user population was identified: pediatric cancer patients. These children needed pain medications and therapeutics which were delivered intravenously. However, over time, their veins could no longer tolerate fluid pushed through their veins. Doctors, patients, and patients’ families faced difficult choices about priority of therapeutics. Developing a needle-less delivery mechanism which used ultrasound enabled the Langer team to reduce the volume of holes in the skin surface to transport pain-relieving therapeutic agents. Langer enrolled hospital doctors and patient families, as well as federal regulators. Because this population lacked solutions to a difficult

problem, federal FDA regulators approved limited human testing. These tests proved positive, and Langer started a company to transition SonoPrep technology to the market.

### Bi-Directional Enrollment and Learning from Soldiers

A third pattern of enrollment was learning from soldiers. The projects focused on materials that became rigid, to make splints or armor on demand, needed input from soldiers who were target users. Three categories of project competed and cooperated. The chemical magnetic actuators project sought materials to respond dynamically to penetrating attack by a bullet or knife. The semi-variable impedance materials project pursued fabrics that could change from flexible to stiff protective armor on demand. The field responsive fluids project envisioned flexible sides in soldier boots and kneepads which soldiers could transform into a splint on demand without needing to carry extra materials.

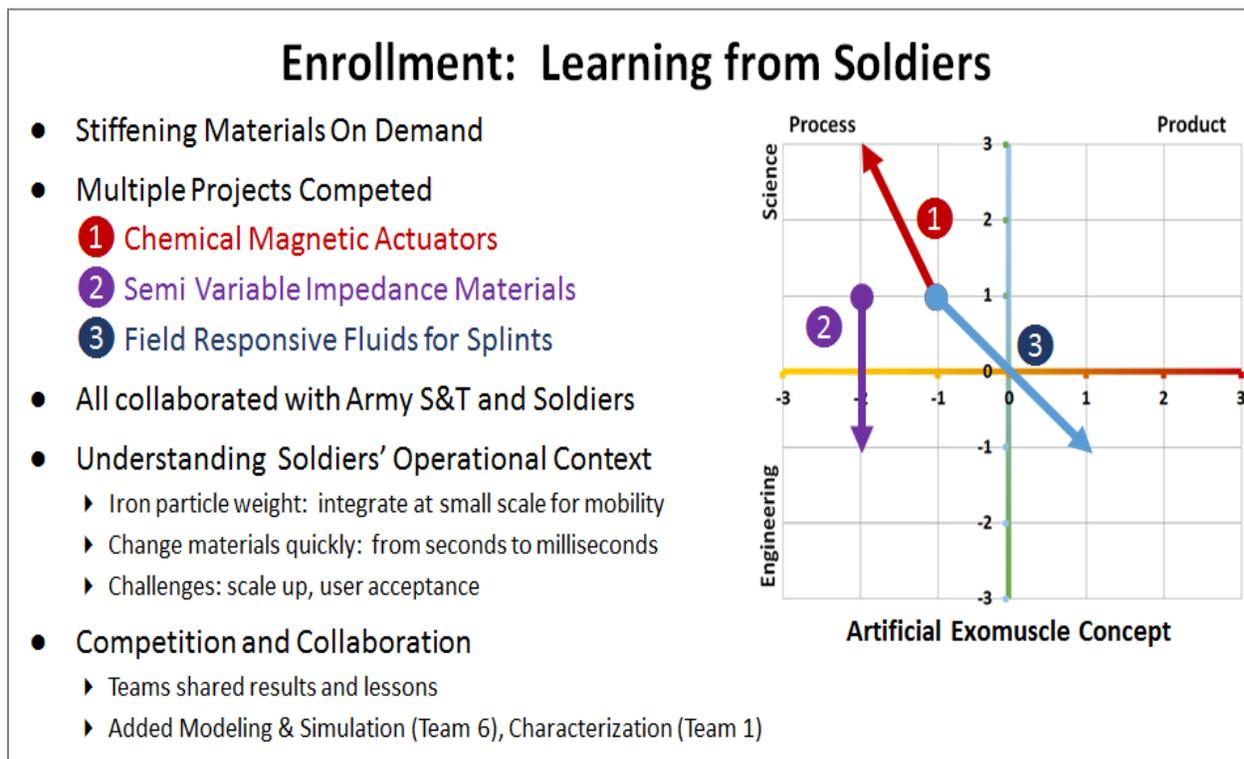


Figure 43. Enrollment: Projects Learning from Soldiers

All three projects started in quadrant II, focusing on process science. The researchers sought to solve the material problem, were without a clear understanding of the soldiers' operational environment. For example, large amounts of iron particles would be heavy if in sufficient quantities to provide protection. The projects shifted focus after all three research teams collaborated with soldiers in Army researchers, and ISN participants visited Army training sites in Louisiana, Georgia, Missouri, and the California desert. Experiencing the soldiers' operational environment caused the researchers to change focus, so materials enabled users to be mobile but protected, and responded in milliseconds to ballistic threats. By meeting the researchers, soldiers learned how to ask S&T researchers for different kinds of protective gear. Bi-directional enrollment and networking brought the communities closer together.

### **Using Enrollment to Accelerate Science to Technology**

A fourth enrollment approach focused on four small teams that operated independently as smaller units, to accelerate science to technology for all their projects. Professor Griffith led a team that created a microfluidic replicant of human organs for medical testing, called 'liver on a chip.' This project started in quadrant I and moved rapidly to quadrant IV with the goal of enabling earlier human testing of biopharmaceuticals. Collaborating with ISN industry partner hospitals enabled researchers to accelerate transitions from science to technology.

A similar microfluidic device by a different ISN research team focused on testing the flow of fluids with potential toxins past microscale sensors. These devices offered the potential for hazard sensors to be built into uniforms or carried by soldiers. This project

team moved rapidly from quadrant II to quadrant IV, quickly transitioning from process to a usable sensor.

Professor Vladimir Bulović led a project to mist electronic materials through vapor deposition onto substrates to create conformally shaped electronic devices. Flexible and resilient electronics have long been sought for Army, astronaut, and first responder uniforms, as well as outdoor recreation uses.

Finally, Professor Barbastathis explored new ways to create three-dimensional objects from flat substrates with techniques derived from origami. His nanoscale-origami projects sought to increase producibility, accelerating from quadrant II to quadrant IV, in order to create devices which exploited properties that change at the nanoscale. The figure below summarizes these projects.

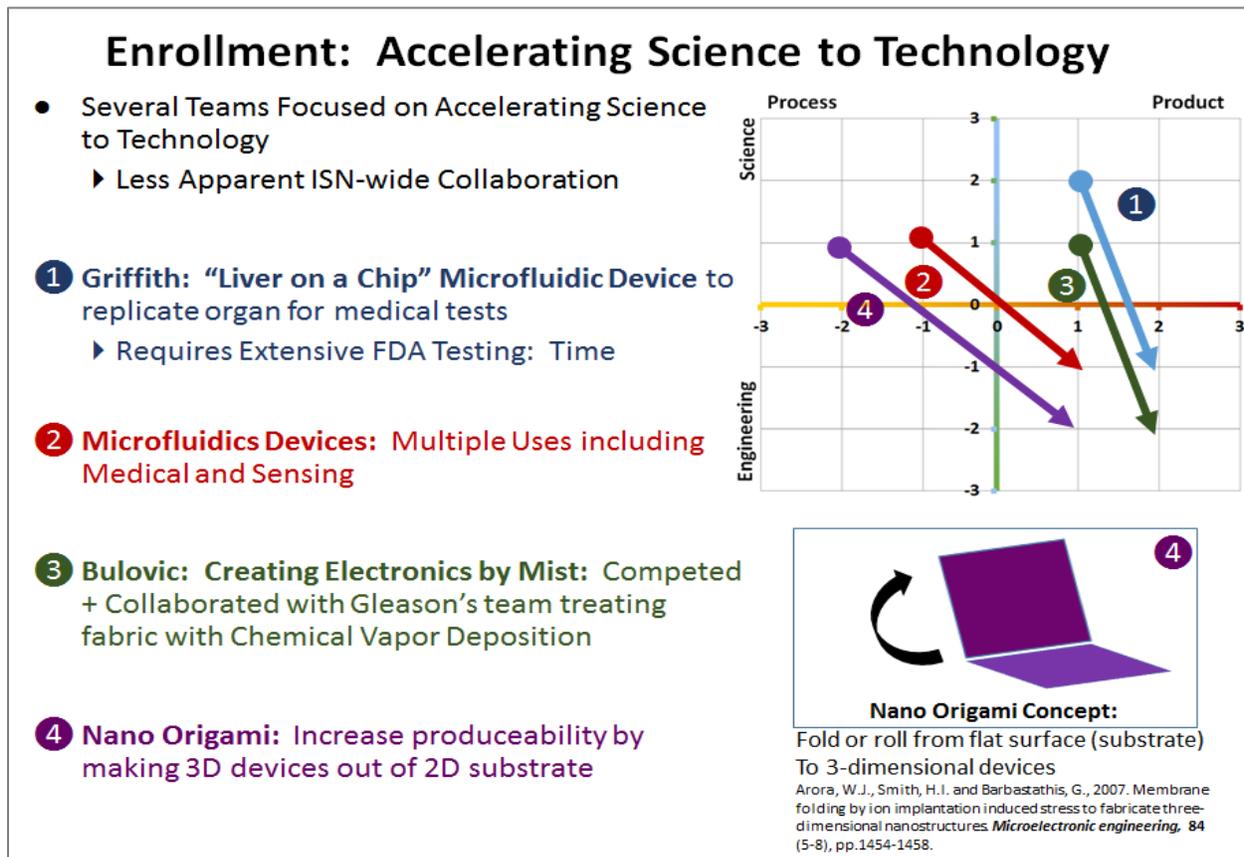


Figure 44. Enrollment: Teams Accelerating Science to Technology

All four projects benefited from participation in the ISN, and close collaboration with Army research sponsors, visiting soldiers, industry, and partners in Army S&T teams. User feedback helped shape and accelerate technology transitions.

### **Using the ISN Soldier Design Competition to Enroll Undergraduates**

A final pattern of enrollment expanded the research community by adding undergraduates through a student prototype competition. MIT was known for entrepreneurship competitions, and the ISN Soldier Design Competition attracted undergraduates who would voluntarily and for no course credit compete to build and demonstrate prototypes to solve soldier challenges – all within six months. ISN leaders saw the competition enrolling students, industry prize sponsors, and mentors from Army graduate students on campus and Army researchers at nearby Natick Soldier Center. The competition proved very successful as a mechanism to attract undergraduates, some of whom became ISN researchers, and gave the ISN positive media coverage. Student teams built prototypes, networked with Army mentors on campus and at Army posts, and created appealing prototypes. Some teams created start-up firms and scaled up manufacturing to sell their products to military and commercial markets. These students translated their knowledge about technology transitions to teach their faculty and fellow students the practical aspects of making technology that made a difference in the world. The engagement was so positive that ISN leaders invited cadets from the US Military Academy at West Point to become regular participants in friendly competition between engineering schools.

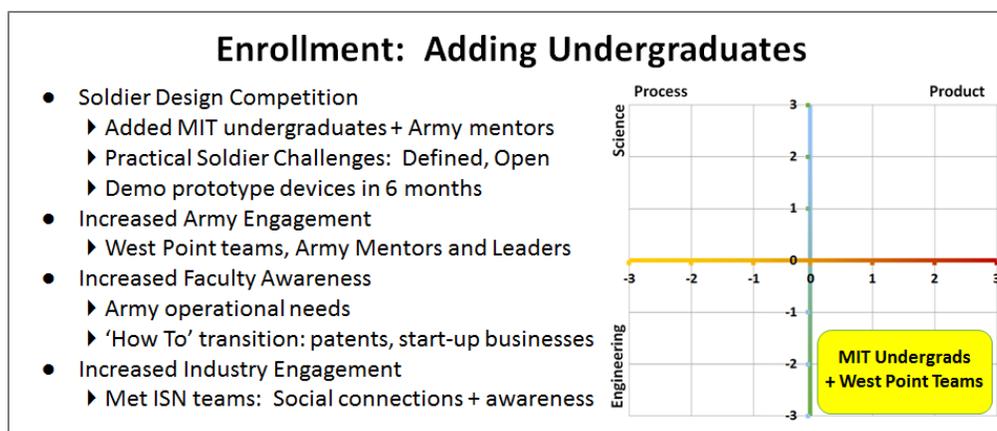


Figure 45. Enrollment: Adding Undergraduates via the Soldier Design Competition

## Understanding the Dynamics of This Research Portfolio

These quantitative measures illuminate some of the inner workings of these project teams. The key metrics point to measurable patterns teams followed to accelerate technology transitions. The quantitative portfolio analysis indicates *that* team positions changed, but needs to be complemented by qualitative analysis to gain insight into *why* positions changed.

When plans changed, the personal impetus may be difficult to discern or detect. For example, people left projects, and the projects ended. Students graduate or leave MIT, as do faculty. When Chemical Engineering Department Visiting Professor Kenneth Beers left MIT in May 2006 to become a consultant, his two projects (6.5 and 6.6) ended with his departure. A change in role could also change level and intensity of involvement in research, as when ISN Founding Director Thomas stepped down in 2006 to become Chair of MIT's Department of Materials Science and Engineering. Some projects were halted by ISN leaders for reasons not made public. Analysis might suggest that the project was not productive, or that a difficult research challenge required regrouping and

refocusing the effort. Sponsors could step in, requesting that a project be put into more restricted intellectual property channels in exchange for their sponsorship.

Defense policy also converged with MIT policy to stop projects. The original ISN proposal included research on camouflage, but that work could become classified, contradicting MIT's requirement for basic research to be open and publishable. Army research sponsors directed funding to specific centers, such as the Institute for Collaborative Biotechnologies, and a flexible computer display center in Arizona. Other projects transitioned to applied research.

Globally, the Department of Defense experienced a profound shift in R&D programs designed to be recipients of technology transfers, with the ending of the Future Combat Systems (FCS) which included the Future Force Warrior technology demonstrator program.<sup>167</sup> FCS was an enormous Army Acquisition System-Of-Systems, networking together 18 Acquisition program products plus Soldiers. FCS planned to procure and field new systems through 2030, and had a budget from 2007-2011 equal to \$25 billion. In 2005, because of rising costs from the Iraq War and Hurricane Katrina, the Department of Defense substantially delayed FCS, and by 2009 the program ended. This meant that conventional war equipment such as the integrated battlesuit was no longer supported, since the war in Iraq required light-weight counter-terrorism gear, primarily procured as commercial-off-the-shelf (COTS) separate 'plug and play' elements. The loss of FCS left many emerging technologies without a transition path. The long-term effect is that Army Acquisition is viewed as a less reliable technology partner; trust is diminished

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<sup>167</sup> Andrew Feikert, "The Army's Future Combat System (FCS): Background and Issues for Congress," Congressional Research Service, August 3, 2009.

- both among external would-be innovators, and by internal Army S&T research sponsors who were left abruptly scrambling without a way ahead.

## Conclusions

Both the qualitative methods of characterizing this technology focused research project portfolio and the quantitative analysis provided different insights. Quantitative analysis can illuminate the generalizable patterns, while qualitative analysis can provide the rich details to understand specifics. Both complement each other to increase understanding of the research.

Research sponsors and participants, partners, and external observers can use these portfolio analysis methodologies to understand the initial portfolio configuration, and to assess the contributions of different research teams. In circumstances where data exists that captures changes over time, portfolio dynamics can be highlighted. In these case studies, the recurring web captures by the Internet Archive provide an invaluable dataset for my descriptive analysis. Potential technology recipients and transition partners can use the analytics as diagnostics, to identify opportunities to reduce obstacles or otherwise accelerate innovations for users. Technology forecasters may apply these analytics in predictive mode. As predictors, these analytics may decrease uncertainty in building out technology roadmaps, or enable analysts to identify potentially unseen emergent technologies. Qualitative analysis can be used in conjunction with these quantitative data science methods, to match the richly detailed specific descriptions with these structural analyses. Analysis can inform evaluation, enabling action at a distance to bring innovations to users.