**Institutional Analysis of Nanotechnology Innovation Network, Phoenix, AZ, USA**

## Part 1: Static Analysis

### 1.0 Collective action

The case of nanotechnology innovation in Phoenix, Arizona, USA is an addition to the original Common-Pool Resource (CPR) database. This CPR report was entered in 2013 by Michael Bernstein at Arizona State University. The nanotechnology innovation network of Metropolitan Phoenix ranks among the top thirty across US cities focused on nanotechnology development. The present case examines the structure of the innovation network, consisting of approximately 400 diverse organizations, between 2011 and 2012. The commons dilemma revolves around managing future risks and benefits from nanotechnology development; the resource is a heterogenous mix of natural and human-made infrastructures.

#### *Background on Nanotechnology*

Nanotechnology refers to materials and chemicals engineered and manufactured at the scale of $10^{-9}$ meters. More than 800 nanotechnology products already exist commercially, serving as preservatives, sealants, or water-proofing agents, or providing structural reinforcement, scratch-resistance.[1] Expert and lay-public discourses are at odds over the trajectory of nanotechnology development (Selin, 2007). Experts tend to advocate caution, focusing more on the potential risks, such as broad environmental contamination across land, water, air, and biologics (Renn & Roco, 2006), of nanotechnology development (Corley, Scheufele, & Hu, 2009). Yet even among experts, camps are split: some urge that society prepare for a techno-utopian future in which nano-bots obviate concerns about illness or even mortality (Segal, 2013); others argue that such visions are fanciful impossibilities (Selin, 2007). Science-fiction-like visions of nanotechnology have captured the public's imagination; the lay-public generally focus on the benefits of continued nanotechnology development (Ho, Scheufele, & Corley, 2011).

Governance regimes of emerging technologies commonly lag behind technology innovation and commercialization (Maynard, 2013). Despite the rapid progress of the field of nanotechnology, in the U.S., efforts of the Environmental Protection Agency (EPA), Food and Drug Administration (FDA), and Occupational Safety and Health Administration (OSHA) are too often understaffed, underfunded, short on appropriate expertise, and ill-suited to match the complexity and uncertainty surrounding governance of nanotechnology (Davies, 2007; Maynard, Bowman, & Hodge, 2011). Further, efforts to advance research, commercialize technology, educate a workforce, and "support responsible development" (in the form physical safety in production, risk communication and ethical, social and legal implications) of nanotechnology (NSTC, 2013), are advancing only piecemeal. The gap created by such a lag creates a vacuum for negative unintended consequences as a technology develops ahead of oversight mechanisms. The present work re-frames the nanotechnology innovation process as a collective action situation[2] involving a

[1] National Nanotechnology Initiative (ND) *Benefits and Applications.* Available at http://nano.gov/you/nanotechnology-benefits. Accessed on 2 December 2013.

[2] This analysis stretches the institutional analysis framework to a non-traditional application, following in the tracks of other work expanding the "commons paradigm" on topics ranging from genetic resource (Hess and Ostrom 2006) to intellectual property and the internet (Bollier, 2005).

heterogeneous community of resource users, a heterogenous resource, a several federal government public infrastructure providers, and a suite of public infrastructures.

### 1.1 The Commons Dilemma/Collective action dilemma

The collective action dilemma is one of innovators self-organizing to minimize the risks and maximize the benefits of nanotechnology development. I posit that the present case reflects a dilemma related to 1) the under provision of infrastructure necessary to minimize the potential risks of nanotechnology development, and 2) the over appropriation of present benefits that accrue to nanotechnology developers. A mismatch exists in which public funds are provisioned (for nanotechnology research) but benefits accrue to select individuals and firms (technology transfer and commercialization). This mismatch makes the non-traditional nanotechnology resource (an amalgam of natural, human, and human-made capital stocks) a rivalrous good at times excludable (patent law protections) and at times non-excludible (open-source research efforts). Because of this complication, I focus a majority of my attention on the collective action, and not the commons dilemma.

### 1.2 Biophysical Context (IAD)

Science and technology scholars generally recognize four phases of nanotechnology development (Renn & Roco, 2006). The first phase corresponds to 2000-2005 and covers passive nano-structures, like inert coatings. The second phase, corresponding to 2005-2010, predicted active structures capable of changing states, as in an energy storage device. The third phase, encompassing 2010 to the present day (2013), heralds more advanced assemblages of active and passive nano-structures, like synthesized, nano-modified viruses. Finally, the fourth phase (2015-2020), known as the development of "heterogeneous molecular nanosystems" forecasts technologies capable of self-assembly and of demonstrating emergent properties (e.g., a human-machine interface that exhibits cognition) (Renn & Roco, 2006). In metropolitan Phoenix, nanotechnology applications include, "personalized medicine, renewable energy solutions, semi-conductors and electronics, automobile enhancements, aerospace and defense, and water filtration" (Foley and Wiek, 2013).

As a resource, nanotechnology is variable and dynamic. A challenge to applying the institutional lens is that nanotechnologies are themselves a combination of multiple forms of infrastructure—ores, precious metals, gasses, water, solar, and fossil energy make up the natural infrastructure; vast amounts of soft-human infrastructure (knowledge, technical expertise, skills, etc.) are also required, along with hard, human-made infrastructure (sterile research facilities, complicated machinery, etc.). Manipulation, appropriation, and use of the resource requires further inputs of human hard and soft infrastructure such as university laboratories and equipment, researchers, federal research funding, venture capital etc. (Foley and Wiek, 2013).

One of the main inputs driving nanotechnology development is money: it is expensive to provision and appropriate the above combinations of infrastructure. Cumulative U.S. federal investments alone, since fiscal year 2001, total some $20 billion (NSTC, 2013). This investment does not include the billions of additional dollars going to transportation, information and communication, and satellite infrastructures that already enable nanotechnology research and development.

Due to the heterogeneous nature of the nanotechnology resource, the provision and appropriation of funding (required to accumulate sufficient infrastructure) seems the most influential attribute of the biophysical system. Focusing on funding has the potential to shift the dilemma from a complex commons case of interacting public, private, and common-pool goods to a collective action dilemma involving the allocation of financial resources for greatest social gain (howsoever defined).

### 1.3 Attributes of the Community (IAD)

The Metropolitan Phoenix nanotechnology innovation network involves approximately 400 organizations. In total, some nine actor groups are represented in Phoenix, including government funders and regulators, academia, businesses, insurance firms, the media, and non-governmental organizations. Key participants in the Metropolitan Phoenix nanotechnology innovation network specifically are academia, industry, and government. At the city level, city government controls zoning and construction requirements that affect the location of nanotechnology incubators (scope rule) (Foley and Wiek, 2013). Industry controls the "distribution, manufacturing, and marketing of products" as well as "the creation of product standards and reliability measurements" (Foley and Wiek, 2013). Autonomy of the industry means that, baring federal regulatory oversight, the resource users in the Phoenix innovation system are also the public infrastructure providers (RU = PIP). Universities act as major research hubs (securing government funding) and provisioners of technology licenses; for example Arizona State University researchers, graduate, and undergraduate students involved in a variety of nanotechnology research endeavors (Foley and Wiek, 2013). The promise of a high return-on-investment is the dominant driver of nanotechnology innovation in Phoenix (Foley and Wiek, 2013).

Private sector entities include large multinational corporations, such as Intel, Honeywell, and Boeing; large nanotechnology firms, like On-Semiconductor, Microchip, Rogers Corp., Abraxis BioSciences; and a variety of medium- to small-size firms. A variety of networking organizations (such as the Arizona Nanotechnology Cluster, Arizona Technology Council, Biotechnology Council) also exist in the Phoenix innovation cluster, serving to connect actors across organizations (Foley and Wiek, 2013). Despite such networking organizations, however, collaboration across nanotechnology sectors (e.g., semi-conductor and water purification) is often a product of personal, informal relationships rather than formal networks (Foley and Wiek, 2013). Collaboration across sectors is minimal, and likely stymied by competition for funding and patents (Foley and Wiek, 2013).

Public sector actors include public infrastructure providers (PIPs) from the Department of Defense, National Science Foundation, National Institutes of Health, Environmental Protection Agency, Occupational Health and Safety Administration, and the National Nanotechnology Initiative. Among these PIPs, the National Nanotechnology Initiative serves as the coordinating entity among federal agencies and is charged with promoting responsible development of nanotechnology (Sandler and Bosso, 2007). Federal PIPs provision technical guidance, research and development funding, and regulations. Examples of the public infrastructure provided by these entities are the small-business innovation research grants and the small-business technology transfer programs created to support business and innovation communities.

Despite the diversity of actors involved in nanotechnology development, the innovation community tends to fracture along lines of specialization. For example, groups involved in the personalized medicine sub-sector of nanotechnology focus exclusively on planning, promoting, and executing, "an innovation policy predicated on personalized medicine. Actors are focused on a specific sector, e.g. personalized medicine, even when discussing collaboration" (Foley and Wiek, 2013). The specialization of the community is reinforced by the nanotechnology-application-based forums established by the Greater Phoenix Economic Council (Foley and Wiek, 2013).

Across the innovation network, two goals loom largest, commercialization (monetary gain) and operationalization (military application), often at the expense of more broadly defined notions of social benefit, or of environmental integrity (Foley and Wiek, 2013). These goals are in-line with the interests of the City of Phoenix to revitalize an economy historically based on agriculture and real-estate development. Much of the nanotechnology community initially developed in the 1960s, with the relocation of the Motorola Corporation to Phoenix, becoming more established in the late 1980s as other high-technology firms joined Motorola (e.g., Intel established Chandler, AZ, facilities around this time). Research by Foley and Wiek (2013) discussed how, "A strong social network of ex-Motorola employees has become today's leading entrepreneurs, patent attorneys, and investors."

Levels of trust in the community seem to vary along domains of nanotechnology specialization, making cross-sector collaboration a challenge. In addition, competition for scarce research and development funding seems to favor individualistic, non-cooperative behavior by businesses or research groups. The presence of some information-sharing networks however, is promising for the potential of future collaboration. At present, seemingly low levels of trust, along with competitive barriers to cooperation, indicate a low potential for actors to solve the collective-action dilemma related to allocation of financial resources for greatest social gain.

### 1.4 Rules in Use (IAD)

#### ***Public infrastructure, monitoring, and enforcement***

Although no new pieces of federal legislation directly cover nanotechnology (Kimbrell, 2009), a variety of soft-public infrastructures are relevant. The Bayh-Dole Act,[3] for example, stipulates that patents from federally financed research may be transferred from the federal government to individuals, research groups, and business university technology offices. Allowances for technology transfer may be part of what makes nanotechnology research commercially viable (information and payoff rules). The absence of a feedback (e.g., a revised scope rule) linking technology transfer to applications with high potential social gain may perpetuate the mismatch in which public funds are provisioned for general research but benefits accrue to small groups of individuals or firms.

The US Environmental Protection Agency (EPA) regulates nanoscale materials under the Toxic Substances Control Act (TSCA), as well as the clean water, clean air, and safe drinking water

[3] For more information, please see this helpful Wikipedia entry on the Bayh-Dole Act of 1980, available at: http://en.wikipedia.org/wiki/Bayh%E2%80%93Dole_Act. Update 11/18/2013 at 06:28. Accessed on 25 November 2013.

acts.[4] The TSCA oversight has four components, a manufacture notice, a significant new use rule, an information gathering rule, and a test rule. The manufacture notice "requires manufacturers of new chemical substances to provide specific information to the Agency for review prior to manufacturing chemicals or introducing them into commerce" (information rule). The significant new use rule requires that appropriators, "Identify existing uses of nanoscale materials based on information submitted under the Agency's voluntary Nanoscale Materials Stewardship Program (NMSP)" (information rule) (note: public comment closed in April of 2013.[5] The planned (as of 2011[6]) but not yet existing information gathering rule of the TSCA, "Would propose that persons who manufacture … nanoscale materials notify EPA of certain information including production volume, methods of manufacture and processing, exposure and release information, and available health and safety data" (information rule). Finally the test rule would, "require testing for certain nanoscale materials materials that are already in commerce"[7] (scope and information rules). The EPA's statutory responsibility is monitored by nonprofit groups; disputes are resolved through the judicial branch of the U.S. government, as recently demonstrated by a 9th U.S. Circuit appellate court ruling that the, "EPA didn't follow its own rules for determining" the safety of a pesticide containing nano-silver.[8]

The U.S. Department of Health and Human Services regulates nanoscale materials through the Food and Drug Administration (FDA). The FDA requires pre-market review of, "New drugs, new animal drugs, biologics, food additives" (USFDA, 2012) (scope rule). Consumer products and pharmaceuticals containing nanotechnologies thus fall under FDA regulation. For products that do not require review, the FDA recommends complying with voluntary consultations, as companies maintain liability for the goods they create (USFDA, 2012). At the state level, Arizona has opted not to regulate nanotechnology until such action is required by federal authorities (Foley and Wiek, 2013).[9]

While coverage of nanotechnology by existing conservation acts is promising, the novel nature of nanotechnology contamination, detection, and remediation present unique challenges. In

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[4] U.S. EPA (2007) Nanotechnology White Paper. United States Environmental Protection Agency Science Policy Council. Washington, DC. Available at: http://www.epa.gov/osa/pdfs/nanotech/epa-nanotechnology-whitepaper-0207.pdf. Accessed in 26 November 2013 p. 78

[5] U.S. EPA (2013) Significant New Use Rules: Certain Chemical Substances. Available at: http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OPPT-2012-0727-0001 Accessed on 22 November 2013

[6] Federal Register 76(117), June 17, 2011: http://www.gpo.gov/fdsys/pkg/FR-2011-06-17/pdf/2011-14943.pdf Accessed on 22 November 2013

[7] Proposed as of 2011. EPA/OCSPP (2011). Office of Information and Regulatory Affairs, Office of Management and Budget. Washington, DC. Available at: http://www.reginfo.gov/public/do/eAgendaViewRule?pubId=201110&RIN=2070-AJ47 Accessed on 22 November 2013

[8] National Resource Defense Council (November 2013) Court Ruling in NRDC's Favor Should Limit Pesticide Nanosilver in Textiles. Available at: http://www.nrdc.org/media/2013/131107.asp Accessed on 22 November 2013

[9] Brewer, J. (2011) EO 2011-05: state regulatory rule making review and moratorium to promote job creation and retention. Available at: http://azmemory.azlibrary.gov/cdm/ref/collection/execorders/id/709. Accessed on 26 November 2013

addition, knowledge of contaminant fate and transport and of toxic effects on human health are little understood, demonstrating the potential need for specific legislation for nanotechnology (Maynard et al., 2011). The seeming lack of revision to rules governing nanotechnology innovation is thus troubling when viewed in context of the larger collective action dilemma of how to minimize the risks and maximize the benefits of nanotechnology development.

*Rules summary:*
For information on position rules, please refer to the section on attributes of community. Boundary rules most commonly relate to the soft human infrastructure (expertise, degrees, etc.) and natural infrastructure that are pre-requisite for nanotechnology innovation. Choice rules are, generally, permission to research, develop, test, and sell nanotechnologies. The few scope rules operating in the system influence existing industrial activity (e.g., compliance with clean water, clean air, safe drinking water, and other acts). The information rules relate to transmission of information on new nanotechnology materials to the EPA, under TSCA, and the FDA. Pay-off rules are embedded in the ability to profit from nanotechnology commercialization, and any legal fees or fines associated with noncompliance with scope rules. Although there are a series of organizations at the Metropolitan Phoenix and Federal levels that convene groups of participants, these participants are able only to change the norms and strategies and not formal rules governing nanotechnology development (formal authority rests with state and federal executive and legislative branches).

**1.5 Nested Action Situations and Nanotechnology Innovation**
The Metropolitan Phoenix nanotechnology innovation network nests within a national network. Cutting across the entire innovation network (metropolitan and federal) are a recognizable series of phases of innovation that progress over time. These phases correspond to discovery, recognition of applications, proof of concept, demonstration of scalability, commercialization, iteration, and disposal/reuse. The outcome of one phase of innovation often feeds into a subsequent phase; different combinations of participants populate each phase. In this way, each phase of innovation process can be thought of as a miniature action situation.

Although it is convenient to think of these phases as unfolding in a linear process, the reality is more nuanced. Restarts, trials, errors, changing conditions, new partnerships, new regulations, technological breakthroughs make for a complex, dynamic innovation process; a change to any of these variables can up-end innovation around a particular nanotechnology application, requiring "a new set of actors with a new set of activities" (Wiek and Foley, 2013). Although efforts to analyze this case focus on Metropolitan Phoenix, further research into each specific innovation phase, as an action situation, might prove valuable for unmoving richer information about attributes of the community, strategies, and norms.

**1.6 Summary**
Nanotechnology Innovation in Metropolitan Phoenix operates successfully, and there is no conventional common-pool resource dilemma. Success of the community, as measured by continued industrial operations and economic profitability, seems related to the presence of strong private property rights, and low regulatory burden. Despite current economic success, there seems to be a collective action dilemma around minimizing the risks and maximizing the benefits of nanotechnology development. Several factors decrease the network's capacity for

collective action, including competitive pressures from scarce funding and a lack of cross-sector dialogue. High infrastructure costs, prohibiting market entry, and a lack of environmental health and safety regulations further hamper the capacity of the network for collective action.

| | Clear boundaries & memberships | congruent rules | collective-choice arenas | monitoring | graduated sanctions | conflict-resolution mechanisms | recognized rights to organize | Institutional performance |
|---|---|---|---|---|---|---|---|---|
| Original Case, 2011-'13 | heterogenous resource poorly defined; profit well-defined | congruence low; appropriators profit, risk externalized | arena's exclusive; appropriators have privileged access | moderate; material challenges present novel monitoring issue | present through existing national regulatory and legal systems | present through existing national legal systems | high; current approach to nanotechnology regulation is self-organizing | robust semi-commons/ semi-private arrangement |

**Table 1**: Evaluation of the current nanotechnology innovation network against IAD principles (Ostrom, 1990)

# Part II. Robustness

## 2.0 Robustness Summary

The institutional analysis of the Metropolitan Phoenix innovation network makes possible a subsequent robustness analysis:

- Innovation occurs among a diverse suite of nanotechnology applications, however there is little connection across these modules.
  - High modularity but low connectivity across modules may make certain nanotechnology sectors susceptible to low-diversity lock-in spirals.
- State rule making "to promote job creation and retention" may make the high-tech sector robust to a narrow definition of profit, but vulnerable to federal-level or other state-level rules that change requirements for commercialization.
  - Robustness to economic growth may expose the innovation system to social or environmental fragilities (e.g., contamination of workers or engineers making production non-viable).
  - Robust pursuit of economic profit may create a lock-in effect in which outcomes have to be commercially viable first-and foremost, reinforcing the above fragilities.

In sum, the high modularity of the innovation network, the low connectivity across modules, and a robust-control for profit make the system robust for economic performance (manage dynamic uncertainty for profit). Such robust nanotechnology profit-protocols are reinforced by a larger, conservative (high resistance to change) capitalist system. Robustness of nanotechnology for profit, however, may increase inequality of the larger economic system and externalize environmental risk, making the system vulnerable to exogenous factors such as economic collapse, environmental feedback/collapse, and pubic opposition/regulatory uncertainty.

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