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Patterns of nanotechnology innovation and governance within a metropolitan area

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ABSTRACT

The present study employs a real-time, practice-oriented, and place-based approach to dissect the process of nanotechnology innovation in support of novel governance schemes. The research question is: What are actors specifically doing in the process of nanotechnology innovation in a metropolitan area, and what are enabling and constraining drivers that could be leveraged for novel governance approaches? The study presents results from 45 interviews and a synthesis workshop with actors from academia, industry, government, and the civil society in Phoenix. Results show that actors follow preconceived mental models of innovation with the primary objective to deploy profitable commercial or military products. The dominant network actors are academics, industry, and government funding agencies. The network is divided along product-based sectors with few cross-sector linkages. Considerable governmental support for entrepreneurs and for academic research via the National Nanotechnology Initiative enables nanotechnology innovation in the early stages. Market failures and corporate barriers, however, constrain the value proposition in later phases. There is novelty in the nanotechnology products; yet, little attention is paid to consumer input, adverse effects, or broader public value generation.

1. Introduction

Cities across the United States currently face a diverse set of challenges from economic stagnation to aging populations and from increasing energy demands to environmental degradation. Technology is commonly used to address some or all of these challenges, including new and emerging technologies, such as nanotechnology [1]. City officials, university researchers, healthcare providers, economic development agencies, private investors and others shape how technologies emerge in the city through decisions taken in the course of their daily activities. Government agencies can regulate laboratory practices in cities, university partnerships with local healthcare facilities offer an opportunity to explore novel technologies, and investors can lure entrepreneurs into moving in or away from a city.

Traditionally, innovation studies focus on specific technological sectors and innovation processes from a macro perspective. Abernathy & Townsend [2] followed innovations in railroad and computer technology with historical analysis. To better understand current activities, scholars have more recently shifted to contemporary studies that address the governance of emerging technologies. Scholars most often analyze national and international level decision-makers [3]. Those levels are often disconnected from places where practical decisions are taken on a daily basis in regional innovation systems [4]. Innovation studies connected to practice often focus on single regulations – e.g. Jaffe [5] explores the influence of the Bayh-Dole Act. Others have focused on isolated

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actors – e.g. Fisher's [6] work with laboratory scientists. Still others focus on transition points between phases – technology transfer from universities to the private sector [7].

However, this body of literature has not taken a holistic approach to couple these "real-world" perspectives including: addressing real-time innovation processes, focusing on the actual decision processes, connecting to the places where they happen and play out. New concepts such as real-time technology assessment [8], practice-oriented analytical approaches [9], place-based technology development [10], and whole product design [11] provide guidance for how to overcome the outlined deficits. A real-time perspective to technology assessment helps to overcome delays between technological innovation and governance efforts [12]. The practice-oriented analytical perspective is based on the obvious fact that innovation happens through people, their decisions and actions within their spheres of influence [9]. From here, we argue that if innovation ought to happen somewhat differently (with somewhat different decisions and actions), namely in more anticipatory and responsible ways, we first need to know *who is doing what (and why) within the innovation process*. The place-based perspective centers on places as 'hubs' where people interact and are 'invested' in life and work; where similar socio-cultural and socio-political forces reign; and where emerging technology arise and transform society. The holistic approach shifts attention away from specialization and segmentation of innovation to a model that accounts for all stages of innovation (c.f. chain-link model Kline & Rosenberg [13]) and thereby allows for more systemic analyses to avoid blind spots by understanding the previous and ensuing consequences of technological innovation.

This study addresses the following research question: What are actors specifically doing in the process of nanotechnology innovation in a metropolitan area, and what are enabling and constraining drivers that could be leveraged for novel governance approaches? This is an intermediate question, which creates the basis to explore how to co-construct governance arrangements and enable responsible innovation [10]. The study applies a simplified framework from institutional analysis [14,15]. The *who*-question identifies key actors, defined as stakeholders with critical roles in the innovation system, and their positions within the nanotechnology innovation process. The *what*-question draws out the activities (decisions, actions, or reactions) performed by the actors. The *why*-question teases out constraining and enabling forces that drive actors to take the actions they take. And all of these questions are addressed from a real-time, place-based, and holistic perspective as outlined above – with the ultimate goal to explore how constraining and enabling forces and actor collaboration could be changed and complemented in ways that would enhance innovation activities in anticipatory and responsible ways. We conducted and analyzed data from 45 interviews and an interactive review workshop with a sub-sample of the interviewees.

Cities have been the nexus of creativity, technical and non-technical innovation, as well as wealth generation for millennia [16]. Hundreds of cities are fostering cultures of innovation, drawing talent, economic opportunity, and recognition to their place in the world as regional innovation centers [17]. Yet, a counter argument to our place-based study could be that emerging technologies are not emerging in *one* place and are, in fact, being shaped by national, international, and even global processes and networks [18,19]. Our approach is not blind to the broader forces operating at higher levels (from a multi-level perspective) than cities, and therefore allows for activities occurring outside this boundary to be captured. Despite a leaky boundary between cities and the broader world, cities continue to be proven leaders and catalysts for regional innovation clustering and economic success [20–22]. Florida [23] points out that a city's "creative economy" is a critical success factor for career options. This reinforces the point that social networks (while maintained in virtual spaces) are forged in real places of learning, recreating, and working – all of which happens in the city.

Nanotechnology, the chosen unit for this study, is an agglomeration of nanoscale science and engineering activities funded by the U.S. National Nanotechnology Initiative [24]. This has resulted in the U.S. Patent and Trademark Office (USPTO) creating a new classification for patents that leverage nanotechnology [25]. Additionally, the search terms that defined by Porter et al. [26] can describe a significant increase in peer-reviewed publications that draw together a diversity of disciplines that intersect with nanotechnology as a common denominator. Further, Youtie & Shapira [27] demonstrate the connection of nanotechnology patenting and publishing with urban innovation clusters.

Metropolitan Phoenix was selected as a case study for several reasons, substantive and pragmatic ones. The first was pragmatic as metropolitan Phoenix offered a unique opportunity for frequent engagement between local actors and researchers to enhance the collaboration, networking, and collective reflection process. Second, city leaders in metropolitan Phoenix are seeking to revitalize the economy by clustering high-technology companies as suggested by Felbinger & Rohey [21]. Third, Phoenix is one of the top thirty nanodistricts in the U.S. [27] and more recently was ranked 18th out of the 358 metropolitan regions surveyed for patents between 2007 and 2011 [28]. The survey results indicate that nanotechnology innovation activities, such as research and development (patents), are elevated in urban areas, which are hubs of knowledge sharing, corporate R&D, and academic research [28]. Fourth, metropolitan Phoenix is home to city, county, and state levels of government involved in technology funding and regulatory activities. Fifth, Arizona State University launched an effort to create a "New American University" with a strong commitment to generate use-inspired knowledge to help solving problems in metropolitan Phoenix [29]. Finally, there are several university partnerships that allow for in-depth analyses of nanotechnology innovation in metropolitan Phoenix, involving, for example those universities, healthcare facilities and private research laboratories fostering personalized genetic medicine. Additional partnerships are dedicated to the research, development and production of nano-enhanced solar energy. There are also collaborative activities that directly explore governance

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issues of nanotechnology. While these characteristics make metropolitan Phoenix a viable case study to explore nanotechnology innovation, it also allows for drawing general conclusions and transferring insights from this case study to other urban innovation districts.

The study's broader purpose is to demonstrate how to create baseline data in support of anticipatory governance and responsible innovation of emerging technologies in general, and nanotechnology in particular. By engaging a diverse set of actors the study also provides opportunities for shared understanding of the current structures and shortcomings in technology governance in metropolitan Phoenix. Finally, the study critically reflects on the added value of a place-based approach to technology innovation.

2. Case profile – technology innovation in metropolitan Phoenix

Phoenix's history is rooted in the technological feat of canal building and the creation of the Roosevelt and Hoover dams, built in the early 20th century, provide water and energy. Two other factors contributed to Phoenix's population explosion – air conditioning and inexpensive housing [30]. In 2010, Maricopa County was the home to just over 3.8 million people and the fourth most populated county in the United States [31]. Today, the five C's (climate, copper, cattle, citrus, and cotton) that defined the first century of Arizona's economic development are up for debate [32]. The study engaged key actors and organizations seeking to reshape the next century of economic development with an emphasis on technology-based industries, including nanotechnology.

Technology-oriented companies took root in the mid-1960s, as the Motorola Corporation relocated to Phoenix. Honeywell, Boeing and other aerospace and electronics firms soon joined Motorola as part of a national plan to relocate military and defense manufacturing sites away from the coasts [33]. In the late 1980s, Arizona State University in Tempe was the home to a flurry of nanotechnology innovations in microscopy [34]. A robust knowledge set and skilled labor force dedicated to semi-conductors flourished. Intel established facilities in Chandler, reinforcing the regions semi-conductor industry, in the 1980s. However, from 1950 to 2005, housing and land development remained the primary economic forces in metropolitan Phoenix [30]. Technology-based enterprises, while certainly valued and recruited from outside Phoenix, were not incubated within the metropolitan region. A positive unintended consequence is that a strong social network of ex-Motorola employees has become today's leading entrepreneurs, patent attorneys, and investors – akin to Avnimelech & Feldman [22] findings. A negative unintended consequence is the large plume of chlorinated hydrocarbons forming the Motorola 52nd Street Superfund Site in downtown Phoenix, a legacy of historically poor waste disposal decisions [35].

Metropolitan Phoenix houses city, county, and state level government, most of which have policies in place to recruit and retain high-technology companies, including companies working with manufactured nanotechnology products. A variety of companies and networking organizations acknowledge working with nanoscale materials as defined by Lindsay [34]. Metropolitan Phoenix hosts a variety of companies and networking organizations engaged in nanotechnology. In addition to Intel, Honeywell, and Boeing, locally based nanotechnology companies include large firms (e.g. On-Semiconductor, Microchip, Rogers Corp., Abraxis BioSciences) and numerous small to midsize firms. The Arizona Nanotechnology Cluster is a networking group that meets monthly in Tempe and Tucson with 20–30 members attending the public lectures on nanotechnology. The Arizona Biotechnology Association runs frequent activities with 25–50 members and conducts larger semi-annual events with hundreds of members attending. The Arizona Technology Council lobbies for technology-oriented companies, publishes a quarterly magazine, and has over four hundred members. They administrated the first Arizona Science Festival in 2012, as part of Arizona's centennial celebration. These organizations are the underlying social network of a community dedicated to technological innovation as a means to support the local economy through entrepreneurial and corporate growth.

As stated above, Metropolitan Phoenix is one of the top thirty nanodistricts in the U.S., based on patent and publication data analysis [27]. Patents issued by the USPTO between 1975 and 2010 (and assigned a nanotechnology classification) were cataloged by Lobo & Strumsky [36]. All patents with an Arizonian inventor were extracted from that dataset, resulting in 152 patents. A census of these patents reveals:

- 17 patents issued to sole authors living in metropolitan Phoenix
- 45 patents issued to co-authors living in metropolitan Phoenix
- 1 patent co-authored between inventors living in two different counties in Arizona, i.e. metropolitan Phoenix and metropolitan Tucson
- 27 patents issued to co-authors, with one party living in metropolitan Phoenix and one living outside of Arizona
- 62 patents issued to an Arizonan inventor *not* living in metropolitan Phoenix

This reinforces the boundary of metropolitan Phoenix as an innovation district with strong internal (45 co-authored patents) and external (27 co-authored patents) collaborations. Phoenix's output of patents is in the second tier of US cities (behind San Francisco, Boston, New York, Philadelphia, and Chicago), similar to San Diego, CA, Austin TX, and others [27]. There is a diversity of organizations (e.g. academic, entrepreneurial and corporate initiatives) working across a number of sectors (e.g. in semi-conductors, defense and aerospace applications, and nano-enabled medicines). The presence (or absence) of actors and sectors is largely unknown and is a point for analysis. Four hundred organizations working directly and in support of nanotechnology innovation make Phoenix a center of activity in nanotechnology were cataloged for this study.

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3. Research design and methods

Guston & Sarewitz [8] first introduced real-time technology assessment and offered the broad research question – *who* is doing *what* – as a means to address innovation activities as they are happening. We ask this question within a framework that adopts the chain-link model of innovation [13] with the additional governance conditions (constraining and enabling) offered by the chain-link model [9]. This model structures nanotechnology innovation as a sequence of phases, linked by process-outcomes, which are bounded by constraining and enabling factors. Based on institutional theory, the framework captures six analytical elements, namely, *nanotechnology application*, *phases* in which *actors* perform *activities* that are shaped by *barriers* and *carriers*. Fig. 1 shows the framework presented to interviewees, the superimposed questions were asked verbally to capture the analytical elements. The impact of the innovation structure used with participant's responses is reported in the results and briefly discussed in closing.

The study draws its participant-based methods of semi-structured interviews and a synthesis workshop from work developed by Wiek et al. [37]. Research was conducted as a case study on metropolitan Phoenix, but incorporated processes outside this geographic boundary, including actors in distant regions (e.g. suppliers), higher authorities (e.g. federal agencies), and global network processes (e.g. for distribution). Innovation activities were mapped by location (within or outside metropolitan Phoenix) to assess the place-based orientation of nano-technology innovation activities in a bi-modal manner.

Interviewees were selected from ca. 400 identified organizations engaged with nanotechnology innovation in metropolitan Phoenix. A sample of 143 organizations from the larger population was randomly selected and solicited for interviews and drew from nine predefined actor groups resulting in responses by: industry (9), academia (14), legal and business consultancies (6), insurance companies (1), government regulatory agencies (2), government funding agencies (6), civic organizations (2), media (2), investment companies (3). A total of 45 individuals from the nine different sectors responded to the solicitation and in-person interviews were conducted at mutually agreed upon locations near their place of employment. All interviewees lived and worked in metropolitan Phoenix at the time of the interviews; yet, many represented organizations transcending the defined boundary as they belong either to higher government levels (state or federal), or to private enterprises with higher levels of organization (national and international).

The interview protocol started with reviewing background information and focused then on the guiding questions of the innovation process framework (Fig. 1). The interviewee was asked to identify *who* did *what* from the 'start' of the innovation process to the 'end'. Participants were encouraged to rebut the presumptions that innovation had a start or an end or distinct phases. Participants first described, in their own words, the innovation process in general, and then illustrated the process with a specific case of their choice.

The worksheets with the interviewer's notes and the transcripts of the interview (37/45 gave permission for audio recording) were analyzed. Worksheets were identified as theoretical or case-specific. Case specific worksheets were grouped by sector (i.e. automotive, medicinal, semiconductor). A researcher coded each analytical component (actors, activities, phases, nanotechnology applications, barriers and carriers). The analysis across the phases was aligned, when it was deduced that a common activity (commercialization) offered a point of alignment across all interviews. After the alignment, the analytical components were clustered by one researcher and validated by a second researcher for inter-rater reliability. Selected interviews were transcribed for quotations to support the clustered data with greater nuance and specificity.

Two months after the interviews were completed, all interviewees were invited to a synthesis workshop held at Arizona State University campus to review the interview results, drew conclusions, and explored future collaborative activities. The workshop had representation from industry,

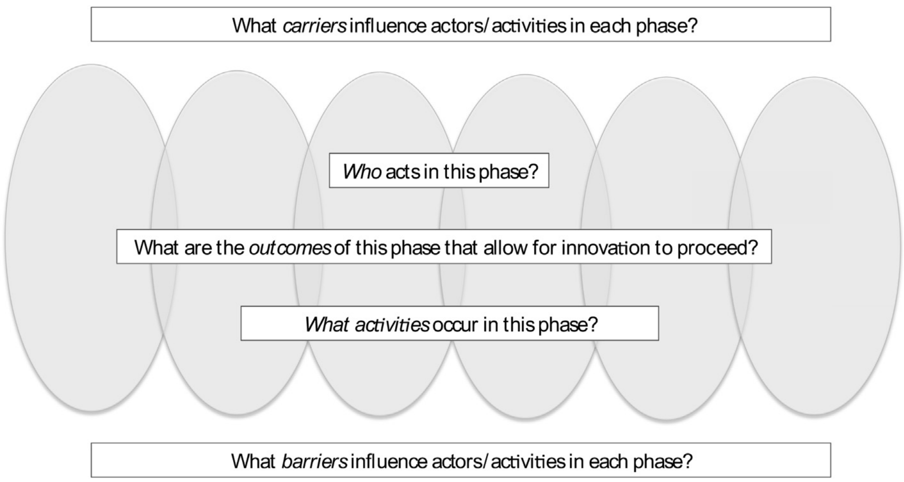

Fig. 1. Framework for eliciting and analyzing data on nanotechnology innovation. (Figure based on: Robinson [9]).

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academia, legal and business consultancies, government regulatory agencies, government funding agencies, and investment companies with 10/45 interviewees participating in the consensus workshop. The workshop consisted of a brief introduction, reporting initial results, and discussion in a semi-structured format. The goal was to review the results of the data analysis with the participants. Participants agreed that the data accurately represented their views on nanotechnology innovation.

4. Results

The rationale for city leaders to support high-technology innovation is clear – it provides an alternative to the rollercoaster land development scheme experienced in Phoenix throughout the past thirty years. Emerging technologies also promise to solve problems that the city faces. But metropolitan Phoenix offers more reasons to engage in high-technology innovation. Arizona has vast solar resources, latent investments in solid-state physics and semiconductor manufacturing, and an affluent retiree community dependent on healthcare services. These are all opportunities around which a culture of innovation is being centered. The rationale for actors to engage in nanotechnology innovation within a metropolitan area is simple but the process of innovation is not. The following sections shed light on the various dimensions of this innovation process.

Results show that actors follow preconceived mental models of innovation and governance (e.g. technology-push, market-oriented, technology-transfer, and closed-collaboration). The findings do not propose a linear innovation model. Rather, the findings report on a complex set of phases that are iterative, dynamic, and overlapping, but nonetheless sequential. Narratives described the iterative activities in terms of restarts, trials and errors, and the repetition of activities within and between the phases. Stakeholders expressed dynamism in the ever-changing conditions, such as the arrival of a new business partner or technological advances that allowed (or prevented) innovation from continuing. Interviewees explained overlaps as moments when the intended outcomes from one phase were accomplished and a boundary was crossed. At that point a new set of actors with a new set of activities were needed. The narratives consistently articulated an originating point and an intended goal and a set of sequential phases that occurred overtime despite the iterative, dynamic, and overlapping characteristics. Stakeholders are situated in a distinct and meaningful sequence that is socially constructed to influence the progression of nanotechnology innovation in particular ways. The study's analytical components reveal the differences between the linear innovation model and the rich and complex sequence described in the narratives.

4.1. Sectorial differentiation by nanotechnology applications in Phoenix

Orchestrated networks of researchers, economic development officers, industry executives, healthcare providers, and corporate investors have coalesced around key nanotechnology sectors in metropolitan Phoenix (Table 1). In

Table 1
Sector-specific nanotechnology innovation in metropolitan Phoenix (number of interviewees who contributed to the respective narrative; out of 45 interviewees) – Phases, dominant activity, and ratio of activities that occur in Phoenix to not in Phoenix.

Sectors	Phase I Initialization	Phase II Experimentation	Phase III Proof of concept	Phase IV Compliance	Phase V Commercialization	Phase VI Endings & new beginnings	Innovation model
Personalized medicine ($n = 13$)	Discovery via research (10:3)	Recognize applications (10:3)	Proof of concept (8:5)	Test & evaluate per regulations (5:4)	Commercialization (5:4)	Iterative innovation (0:5)	Linear model
Renewable energy solutions ($n = 10$)	New idea or concept (5:4)	Recognize applications (7:3)	Proof of concept (5:4)	Bring on early adopters (2:4)	Commercialization (5:2)	Operation and maintenance (3:3)	Technology transfer
Semi-conductor & electronics ($n = 10$)	Identifying market (5:5)	Experimentation (8:2)	Assess market (8:2)	Bring on early adopters (2:7)	Commercialization (3:6)	Disposal or recycling (2:5)	Market pull
Automobile enhancing ($n = 7$)	Discovery via research (5:1)	Recognize applications (5:2)	Proof of concept (4:2)	Meet scalability challenges (3:4)	Commercialization (1:4)	Financial exit (4:1)	Linear model
Aerospace and defense ($n = 6$)	Identifying problems (2:3)	Analyze the problem (3:2)	Solve the problem (3:2)	Test & evaluate per regulations (2:4)	Operationalize (2:3)	Mitigate new threats (0:4)	Closed collaboration
Water filtration ($n = 3$)	Discovery via research (3:0)	Recognize applications (3:0)	Proof of concept (2:1)	Meet scalability challenges (0:2)	Commercial-ization (0:2)	Iterative innovation (0:2)	Linear model
Overall ratio	30:14	36:12	30:16	14:25	16:20	9:20	

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personalized medicine a technology roadmap was created to stimulate economic development and secure investments from academia, government and private funders [38]. This roadmap illustrates how actors are organizing themselves based on the geographical unit of the city (metropolitan Phoenix) to plan, promote, and execute an innovation policy predicated on personalized medicine. Actors are focused on a specific sector, e.g. personalized medicine, even when discussing collaboration. They do not refer, in any significant way, to other sectors of innovation. This makes it difficult to pull actors apart from the specific technological and economic goals of their product-based sub-network, as seen in the statements below.

> "[He] wanted to come back to Arizona after running the [program] at NIH. And so just a handful of people [names removed] started building the thematic area." (Private investment group)

> "The [Company] stopped the testing. So I called [Company President]. I have known [him] for quite some time. With a half a million deaths, you are talking about a million women at risk of dying. Why did they stop pursuing the drug? Because they ran out of money, […] I didn't want them to stop a thirty-two patient study." (Academia/Research)

The sub-networks of personalized medicine and renewable energy meet separately in sector-based forums organized by the Greater Phoenix Economic Council [39]. These types of social structures divide the nanotechnology innovation network along product-based sectors. This limits overlap and synergies between sub-networks, creating disconnects in the overarching governance regime.

The actor network centered on personalized medicine and engaged with nanotechnology applications also exemplifies the myopic focus on commercialization as the sole mechanism to bring value to the public. Table 1 illustrates that despite the sector (i.e. solar or personalized medicine), the terminal goal is always commercialization (Phase V). Defense applications are the exception, where the term is operationalization, bringing nanotechnology into military operations. Such a commercialization-oriented governance regime of nanotechnology innovation fits into the "economics of technoscientific promise" [40]. Nanotechnology innovation as currently conceived is attempting to leverage techno-scientific promises into economic benefits. This characteristic defines the orientation for all theoretical and empirical expressions of nanotechnology innovation by the participants. Participants mentioned social benefits as the secondary outcome that resulted from commercialization. No one discussed a non-commercial means to realizing social benefits, such as the efforts by the late Joseph Salk (among others) and the World Health Organization to globally distribute a polio vaccine as a social good [41].

The city, a place-based organizing mechanism of nanotechnology innovation, is comprised of six differentiated sectors where more than one interviewee provided an empirical narrative. The six cases are personalized medicine, renewable energy solutions, semi-conductors and electronics, automobile enhancements, aerospace and defense, and water filtration (Table 1). The interviewees specified innovation activities occurring in metropolitan Phoenix and not in Phoenix. This place-based analysis shows that in metropolitan Phoenix, the greatest opportunity for influence by the actors within the region is "upstream" – in the first three phases of innovation. The ratio shifts after that to activities outside of Phoenix, signaling regional actors have less control over commercialization.

Analyzing the data by product sector demonstrates a strong alignment with the different 'ideal-type' innovation models, shown in the right-hand column of Table 1. The provided framework (i.e. Fig. 1) offered the flexibility for alternative "mental models" [42] to emerge, yet consistency among stakeholders within a given product sector is observed. The innovation models are expressed as much through the inclusion (or exclusion) of actors, as in the originating activities in the initial phase (i.e. based on market signals, scientific discovery, or identifying problems), and the enabling and constraining conditions that guide the innovation process, e.g. closed collaboration relied upon early government funding from mission-oriented agencies that resulted in military products restricted by purchasing agreement with government buyers.

4.2. Sequences and phases of nanotechnology innovation

The interviewees provided 17 general and 49 case examples for innovation sequences. As mentioned above, all but two pathways lead to commercialization and differences appear in the wide variety of actions taken to achieve commercialization. The most frequently mentioned activities, actors, barriers and carriers for each phase are presented in Table 2.

Clustering all 66 innovation sequences results in four distinct types or "mental models" [42] of nanotechnology innovation (Table 3). Only two of the forty-five interviewees created an alternative model, than the one provided – the "funnel model" that he learned at the Sloan Business School and other participant drew an "*S*-curve" model and talked about four phases along that model. Neither alternative disrupted analysis, post interview, as the six analytical components were systematically captured.

The most prominent progression of activities by phase, based on the highest frequency of mentions by participants, can be labeled as "linear innovation" or "technology push": discovery, recognizing applications, proof of concept, demonstrate scalability, commercialization, and iterative innovation. This mental model of innovation aligns almost perfectly with the early innovation model suggested by Abernathy & Townsend [2]. The second most dominant model is "market pull" [43], where the market demands innovation. The third is the "technology-transfer" model. This aligns with the idea that academic knowledge is leveraged by small private firms (run by entrepreneurs), before the technology (or company) is scaled up and distributed by large corporations [44]. The fourth is the "closed collaboration" innovation model, whereby a client (e.g. Department of Defense) seeks to solve a problem and collaborates with innovative firms to execute the solution. It is important to note that all sequences are ideal-typical

Table 2
Phase-specific activities, actors, barriers, and carriers considered critical, based on high frequency of mentions (number in parenthesis) in the nanotechnology innovation process in Phoenix.

	Phase I Initialization	Phase II Experimentation	Phase III Proof of concept	Phase IV Compliance	Phase V Commercialization	Phase VI Endings & new beginnings
Activities	Discovery via basic research (21) Developing new concepts (18) Identify problem (13) Identify market need (8)	Recognizing application (40) Experimentation (16) Problem analysis (4)	Proof of concept (34) Assessing market potential (21) Problem solving (3)	Demonstrate scalability (30) Bring on early adopters (20) Test & evaluate (7)	Commercialization (40) Operationalize (3)	Iterative innovation (25) End-of-life (9) Financial exit (3) Mitigate new threats (3) Repair – O&M (2)
Actors	Academic researchers (33) Entrepreneurs (30) Large corps. (22)	Entrepreneurs (33) Academic researchers (31) Federal funding (23)	Entrepreneurs (26) Large corps. (19) University tech transfer (16)	Large corps. (23) Federal non-funding (17) Venture capital (15)	Large corps. (37) Federal non-funding (15) Consumers (12)	Large corps. (21) Federal non-funding (8) Consumers (7)
Barriers	Government barriers (24) Entrepreneurial constraints (18) Corporate barriers (18)	Entrepreneurial constraints (19) Private funding failures (18) Market failures (14)	Entrepreneurial constraints (22) Private funding failures (20) Technical risk (16)	Market failures (25) Government barriers (22) Technical failure (14)	Market failure (21) Corporate barriers (20) Government barriers (14)	Market failures (5) Corporate barriers (4) Technical failures (4)
Carriers	Entrepreneurial capacity (53) Government assistance (35) Academic capacity (24)	Entrepreneurial Capacity (40) Government assistance (31) Academic capacity (30)	Entrepreneurial capacity (28) Academic capacity (25) Private funding capacity (21)	Government assistance (21) Technical capacity (20) Corporate commitment (20)	Market drivers (21) Corporate commitments (20) Government assistance (19)	Market drivers (15) Government assistance (5) Legal mechanisms (4)

and interviewees recognized iterations, dynamism and overlap between phases. And yet the ideal-type models that emerged through the narratives have clear differences among the activities, actors, barriers and carriers in each phase of innovation, see Table 3.

4.2.1. Phase I – Initialization

The first phase is labeled "initialization" (similar to "research and exploration" in Robinson (2009)) in which actors set in motion endeavors to pursue nanotechnology innovation. Nanotechnology innovation is initiated through exploring phenomena and new concepts that address the nanoscale, identifying market needs, and identifying problems, usually through the lens of a specific sector (e.g. water, energy, medicinal). The tangible outcome is an initial, often unspecific and fairly vague nanotechnology application concept (often more defined by a need or a problem than by a solution). Government funding agencies, academic researchers, and industry dominate the initialization phase of the innovation process (Table 2).

Primarily, academic and industry researchers with specific expertise, skills, and competence are given access to specialized equipment, owned by universities, research institutes, or corporations, and receive assistance through direct funding, tax credits, space, etc., often from government agencies. They express their work as:

> "trying to do fundamental science to understand what makes that nanoparticle unique or different. We come to that problem with a motivation of sustainable energy, but not with an intention to develop sustainable energy." (Academia / Research; no. 3)

In this way, they attempt to make discoveries, develop ideas, and identify problems, based on previous research and, at times, motivated by societal values.

Nanoscale scientists and engineers working in public and private organizations receive substantial funds from federal agencies, the top three being the Department of Defense, National Science Foundation, and National Institutes of Health [45]. This is often reflected as:

> "[NSF and NIH] are establishing research priorities and putting out topics to scientists to solve the grand challenges of the day. I am not sophisticated in debating things like research direction, who decided what, and gets researched upon. […] Program officers put out topics and calls." (Academia / Leadership & Support; no. 2).

This asserts that decision-making processes (RFPs, proposal review and selection, etc.) within funding agencies shape the research agenda, research prioritization, and research design of public and private research organizations accordingly.

Alternatively, private entrepreneurs and business-oriented professionals develop new concepts, often based on identified market needs with funding enabled through private networks or federal grants, such as the small business innovation research (SBIR) and the small business technology transfer (STTR) program. Receiving either of these grants is a game changer:

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Table 3
Key features of nanotechnology innovation models.

	Linear model	Market pull	Technology transfer	Closed collaboration
Activities sequence	1. Discovery via research 2. Recognize application 3. Proof of concept 4. Meet scalability challenges 5. Commercialization 6. Iterative innovation	1. Identify market 2. Experimentation 3. Assess market potential 4. Bring on early adopters 5. Commercialization 6. Iterative Innovation	1. New ideas/concepts 2. Recognize application 3. Proof of concept 4. Bring on early adopters 5. Commercialization 6. End-of-life	1. Identify problem 2. Problem analysis 3. Solve problem 4. Test & evaluate 5. Operationalization 6. Mitigate new threat
Main actors	1. Large corporations 2. Academic researchers 3. Entrepreneurs	1. Entrepreneurs 2. Large corporations 3. Federal non-funding	1. Academic researchers 2. Venture capitalists 3. University technology transfer	1. Federal agencies (DOD) 2. Large corporations (defense contractors) 3. Academic researchers
Main barriers	1. Government barriers 2. Technical risks/failures 3. Market failure	1. Government barriers 2. Entrepreneurial constraints 3. Market failure	1. Private funding failures 2. Corporate barriers 3. Market failure	1. Government barriers 2. Technical risks/failures 3. Corporate barriers
Main carriers	1. Entrepreneurial capacity 2. Academic capacity 3. Corporate commitment	1. Entrepreneurial capacity 2. Corporate commitment 3. Market drivers	1. Government assistance 2. Academic capacity 3. Private funding capacity	1. Government assistance 2. Technical capacity 3. Corporate commitment

> "All I had was a volt meter. But now that I was getting money from the [government agency], I had to throw in money. In my house, I built a room and bought equipment. Then, they wanted to visit the lab and it started to get real." (Industry; no. 1)

While expertise, funding, and networks are strong enabling factors in the initialization phase, there are barriers to good ideas, such as short-term oriented problem-solving mandates, even within academic institutions. A member of the technology transfer department expressed it thusly:

> "We have a problem. Solve the problem! If I want to get promoted this year or next year, I have to work on short-term problems and short-term solutions. There is no effective compensation scheme […] that allows ten years to produce results." (Academia / Leadership & Support; no. 3)

There are also historical barriers that reflect the local socio-cultural context in which nanotechnology innovation in metropolitan Phoenix takes place:

> "The history of successful land speculation begs the question, why would you invest in nanotechnology? Why take that risk?" (Consulting Firms / Legal & Business; no. 2)

> "And that is kind of where Phoenix is today, in its evolution, comparative to the San Jose area or Boston where they have gone through this process. We have never really gotten to the point to have an exit strategy for the investors. We are still young." (Media; no. 1)

Academics and entrepreneurs face a lack of local venture capital attuned to emerging technology, including nanotechnology. However, recent innovation activity demonstrates metropolitan Phoenix is among national innovation leader [27,28], despite the barriers.

4.2.2. Phase II – Experimentation

Similar actors, those with highly specialized expertise, strong problem-solving skills, and creativity leverage all their assets to move ideas forward. They seek to refine and apply initial concepts and solution options. The tangible outcome is a refined nanotechnology application concept, at times even a prototype, which holds the promise of value. This phase orients the innovation efforts by recognizing and exploring nanotechnology applications within specific sectors (e.g. semi-conductors) and receiving application-oriented funding and support.

Academic researchers and private entrepreneurs recognize applications of knowledge and experiment with technological ideas, for example:

> "We noticed a particular characteristic of the material we were working with. We were trying to build a sensor and we discovered it had a failure mode because of the electro-chemical processes at the nanoscale. […] we recognized we could use this failure mode. It could be applied in solid state memory." (Academia / Research; no. 1).

Entrepreneurial efforts without strong institutional support and a dearth of private funding are held in tension between an individual's capacity and limitations (Table 2). Entrepreneurs boot strap and move forward, relying on themselves and their (social) networks. They work out of laboratories located in garages, in the corners of old office buildings, and equipment is rented or borrowed from larger organizations. One entrepreneur depicted the advances in these terms:

> "We have found out how to make nano-powders differently and better. We had to experiment with plasma guns. First we had to build the gun and the collection system to capture the nanoparticles. (Industry; no. 3)

Federal research funds, university laboratories, equipment, and inexpensive graduate researchers are the primary supports for academic researchers. Yet, to receive federal funding, the funding request must align the proposed research activities to, "facilitate continued progress in nanotechnology and to encourage ready access to state-of-the-art research capabilities for accelerated commercialization efforts" [46]. This presents a significant barrier to pursue diversified research agendas and orients the value proposition of nanotechnology toward commercial markets. Statements such as this reflect this barrier:

> "[Corporations] will actually help write topics with the agencies, calls for radio applications, space application, or this UAV [unmanned aerial vehicle] application. Let's write a topic for that and start marching that up the technology readiness curve. (Academia / Leadership & Support; no. 2)

In the experimentation phase, trial and error, modeling solutions and testing new materials leads to nano-enabled applications that are valued by funding agencies, corporations, and venture capitalists. With this valuable application delimited, the next phase seeks to manifest a prototype to demonstrate that the applications work.

4.2.3. Phase III – Proof of concept

In this phase, the intended goal is to prove the nanotechnology is functional and markets exist. Achieving this goal is required to move nanotechnology out of the lab. For university-initiated research this requires a transfer into private ownership. University technology transfer offices license nanotechnology [46], in accordance with the Bayh-Dole Act [49]. Proving that a market exists and a return on investment will be achieved if financial commitments are made to the prototype can been called "up value science and technology findings" [9].

Academic researchers and R&D staff prove technical concepts, whereas market-oriented partners prove market value in the following ways:

> "You start out with a team of market experts - strategic marketing team and a technology team and once you agree what you are going after you hand it to the technologists and say prove it." (Industry; no. 3)

In this phase, individuals may change roles as the prototype is taken out of the laboratory. However, a lack of training, prior to this transition, creates numerous entrepreneurial constraints. One entrepreneur described it this way:

> "I teach during the day, but my company is this. Everyone knows – oh that is [professor's name removed] company … can I keep up with both?" (Industry; no. 5)

For researchers at public universities, a critical step in this phase is the licensing of the nanotechnology application. Technology transfer offices leverage academic capacities, while playing multiple roles that go beyond simply transferring licenses. They coach academic researchers, run interference and negotiate contracts, file patent disclosures and applications. These activities are beneficial to some and present barriers to others, depending on whom you ask:

> "The tech transfer […] functions as an impediment. If you ask them, they are not. If you ask anyone else in the world, they are." (Private investment group; no. 1)

On the other hand, technology transfer offices may give researchers preference in licensing decisions, even if the university is offered more money by a corporate interest – which is *not* in line with published work on technology transfer as a mechanism for university profit [47,48]. One researcher expressed gratitude for these informal policies:

> "They [technology transfer officers] did a great job of running interference with bigger companies to help our venture out of the laboratory. They put us in the driving seat, so to speak." (Academia / Research; no. 1)

Yet, there continues to be a high level of technical and financial risks including:

> "One of the challenges of some of the areas like semiconductors, nanotechnology … it takes huge sums of money to get over the technical risk and you still have the marketing risk." (Consulting Firms / Legal & Business; no. 5)

Once the technology is licensed from the university it requires private investors to hire technical personal, pay for access to high-cost equipment and test nanotechnology prototypes to ensure functionality of the initial product. An investor offered this perspective:

> "Now that they are out of the lab, they are looking at the reality, get money or die. " (Private investment group; no. 1)

Apart from fundraising skills, particular expertise held by experienced business executives and consultants is needed to integrate laboratory prototypes into the buyer's systematized production process. The prototype needs to plug into the socket, to fit within the pre-defined systems of production. In the next phase, coming into compliance with established sectorial systems dictate the innovation's ongoing success, e.g. in medicine, semi-conductors, or automobile manufacturing.

4.2.4. Phase IV – Compliance

Struggles between regulators and regulated companies; between industry standards and novel products; and between institutional buyers and technology developers best describe this phase. Tangible outcomes include receiving a notice of compliance from the regulating agency; meeting (or changing) industry standards; and scaling the manufacturing capacity to meet anticipated client-demand. Regulatory affairs departments, product engineers, insurers, and legal consultants (among others) prepare requisite forms to initiate the different approval processes between the sectors. Approval processes, while conceived of as a barrier, are also an enabling force; if your product receives approval, future profits are close at hand and protected by the very barrier the product just overcame.

When attempting to transform prototypes into mass-produced goods, the reliability and consistency standards in semi-conductors and electronics often result in technical failure. Yet, structuring a competent team of venture capitalists and corporate investors with strong technological capacities can enable success as evidenced here:

> "We are talking $40 million. They brought in a dream team of investors and companies that contributed equipment. They brought in fabrication facilities. They

are supplying engineering samples now and customer samples near the end of the year. You need to bring up the yield to the high 90 percent, so that most of your products work, you bring up the reliability by [testing environmental conditions], and then you have qualification, which means you can hand someone a data sheet that tells the customer what the product does." (Academia / Research; no. 1)

Federal buyers, primarily the Department of Defense, support an alternative model, which finances repeated testing and evaluation cycles that push prototypes to the breaking point and beyond termed 'spiral innovation'. 'Spiral innovation' is described as:

"From the initial prototype – we did spiral development. We spiraled through a series of exercises. After each spiral we would sit down and do an evaluation. Is it possible or not? Go think … At the completion, the [military technology] became the program of record for the Army. (Industry; no. 8)

Regulatory agencies review submitted applications for approval. In the United States, while many regulations intersect with nanotechnology, no formally adopted policies (to date) explicitly address the risks unique to products containing nanotechnology [49]. The Food & Drug Administration (FDA) is struggling to adjust existing policies to the complexities of nanotechnology-based drugs and devices [50]. Meeting FDA approval standards, which are not yet specific to nanotechnology, is a significant barrier as described by an attorney:

"They are very small, investor-funded and so they have limited capital. They are located here in the Valley and they are sitting here having heard nothing from the FDA. And finally out of shear frustration, they have an attorney write a letter to one of the senior FDA officials. And it basically says, I have a client that is burning $200,000 a month and we can't get the courtesy of a response [...] The point of the story is to demonstrate the real barriers that one can have. I had that conversation this morning." (Consulting Firm / Legal & Business; no. 5)

The renewable energy sector struggles with the well-known market barrier imposed by existing energy prices coupled with a lack of government subsidies and tax breaks [51]. Government agencies, industry standards, private-public collaborations, and market barriers all constrain the product portfolio of nanotechnology.

4.2.5. Phase V – Commercialization

In this phase, large corporations drive *commercialization* through profitable sales and consumers expect to reap value through the use of nano-enhanced products and services. The activity, operationalization, is the language used by defense contractors and government agents for military and security agencies. Large corporations perform a number of activities, including:

"You start selling stuff, that is the good part. You have to do the sales and marketing. Hopefully you have done that work upfront, certainly the investors have done that work. You become focused on driving down costs and hitting your sales targets. […] [Who is doing this?] Those are your legit companies, larger companies, if you are going to get something to your consumer. You need the big financial backing" (Industry; no. 5).

These activities fall under the umbrella of commercialization, including marketing, sales, manufacturing, and distribution.

This phase is not free of market barriers, especially for small-medium enterprises (SMEs), as stated:

"If we really truly have game-changing technology that can truly upset the apple cart that gets better performance […] then you have the challenge of competing with the big boys. You have seventy-five years of experience with the previous technology and no proven cost of manufacturing the new product at full-scale commercialization. […] It has to be much better than what they are using today." (Industry; no. 3)

These barriers persist even if all previous regulatory, technical, and initial market barriers have been overcome.

Federal agencies play multiple roles; the US Department of Health and Human Services (DHHS) is an example. DHHS houses the NIH, a top nanotechnology funder in medical research [46] and the FDA, which holds responsibility for regulating all medical devices and pharmaceuticals. These two roles create an ethically contested decision-making framework [52]. Monitoring of approved pharmaceuticals is regulated by a variety of international organizations, exemplified here:

"In terms of the commercialization of the product, we are heavily regulated. […] This facility will supply products worldwide. The three big agencies that we have to answer to are the FDA here in the US, the MHRA in the EU and the Japanese authorities." (Industry; no. 6)

Outside of the medical sector, there is less clarity regarding the protection of human health and the environment. Without clearly defined roles between the actors, there are some divergent perspectives on this issue, as illustrated:

"Unions train workers on issues of environmental health and safety." (Consulting Firms / Business & Legal; no. 2).

"Federal regulatory agencies protect worker health and safety." (Industry; no. 6)

Alternatively, the role of protecting human health and the environment will not be addressed by Arizona state agencies due to a moratorium on new rules, implemented via executive order [53]. The executive order allows state agencies to create new rules only when required by federal statute, articulated by the director of one state agency:

"We will not regulate nano, unless the feds make us." (Government regulatory agencies; no. 1).

The executive order is justified as a means "to prevent additional and unnecessary burdens on our private sector employers [from] a regulatory explosion detrimental to job creation and retention in this State" [53].

Despite evidence indicating citizens worry about nanotechnology risks [54,55], our study did not produce specific indications about citizens' product feedback, preferences, concerns, risk perception, or social amplification of risk in metropolitan Phoenix. Citizens are largely absent from the innovation process (see Discussion below).

4.2.6. Phase VI – Endings and new beginnings

Two clearly divergent perspectives appear in this phase. Endings include the artifact's end-of-life, the technology is eclipsed, or a financial exit occurs (Table 2). New beginnings are iterative innovations and the emergence of new ideas (starting a new innovation process through initialization). Mostly, large corporations are re-inventing products by adding features and benefits or seeking process changes that achieve higher profitability. Market drivers support iterative innovation and facilitate a feedback and response mechanism between customers and large corporations. And while market failures occur, this relationship enables corporations to continue to reap financial rewards and drive production. It offers consumers a limited way to enhance the features of a product. One consultant described this case as an apt example:

> "Two projects led to an idea in our research group to combine these ideas and build upon the concept of Chinese handcuffs. We applied that to airbag technology. [...] 70% of all deaths in side impacts are the result of head injuries. We sold that to [German Automobile Company]." (Consulting Firms / Business & Legal; no. 1)

Consumers ultimately dispose the nano-enabled products (recycled, landfilled, etc.) and the regulation of these activities is held by federal regulatory agencies. The majority of nano-enabled products are not yet designed to facilitate repair – they are designed with replacement in mind, as indicated in the iterative innovation described above. Few considered the product's end-of-life and those who did offered little insight into waste management strategies:

> "It is commercialized into obsolescence, right. It continues to exist until it is no longer valuable and nobody wants it, then it is sun-setted and dies and goes to nano-heaven." (Consulting Firms / Legal & Business; no. 5)

Few service firms perform long-term operation, maintenance and repair of the artifacts that will need to perform in the environment.

> "Today, now we are getting into next generation thin-film testing and this is where it gets to the nano piece. As PV evolves [...] into a more sophisticated platform, they are setting up suites in the sort of nano testing area." (Academia / Leadership & Support; no. 2)

This exemplifies the short-term nature of the nano-enabled products under development.

4.3. Innovation stakeholders

An overarching look at the constellations in the actor network of nanotechnology innovation in metropolitan Phoenix reveals important features of the current governance regime [37]. Academic, industry, and government actors dominate nanotechnology innovation in metropolitan Phoenix (Table 3) – reinforcing the importance of the "triple helix" actors [56]. The government, at the urban scale, plays various roles throughout the innovation process. City governments are critical for land development and building construction easements; zoning and permitting provided by ombudsman services; to spending significant public funds on the creation of technology incubators. Similarly, industry performs a wide array of activities from the distribution, manufacturing, and marketing of products, to the creation of product standards and reliability measurements, and they pose barriers through market domination and pricing regimes that prolong incumbent technologies. Lastly, universities perform a variety of activities from researchers bent on exploring material properties and recognizing applications to technology transfer officers weighing options for licensing agreements to executive staff pre-selecting projects submitted to federal funding agencies.

Nanotechnology in Phoenix is a closed innovation system (see Almirall & Casadesus-Masanell [57] for a discussion of open and closed innovation). It is the exclusive domain of expert professionals operating within product-based sectors. There are coordination efforts, but only within the sub-networks, as seen in this series of short statements:

> So I called [President of Company]. I have known [him] for quite some time." (Academia / Research; no. 5); "He was a really good friend." (Industry; no. 1); "I have known her for years." (Industry; no. 6); "It is all about the relationships." (Government funding agency; no. 2) [All statements are from people working on personalized medicine in Phoenix.]

Despite collaborative efforts within product-based sectors, competition is a dominant feature not only in business but also among universities, for example. Many perceive this as detrimental:

> "This [collaboration] doesn't happen because everyone is keeping their work close to their breast. Heaven forbid someone else gets your funding! We don't necessarily tell each other what we are working on. So, [one university] could have the missing piece that [another university] needs, but there is no easy way to look that up. You just need to hope you know the right person so you can ask." (Consulting Firms / Business & Legal; no. 3)

Competition between different city governments in the metropolitan area is just as intense.

> "You don't talk to people in [city name] about who you are recruiting." (Government funding agency; no. 5); "There is no mechanism for the cities to collaborate and work together." (Government funding agency; no. 1); "We are out competing [city] for the best jobs, the high-tech companies, we are leading." (Government funding agency; no. 3)

This infighting hampers the metropolis as a collective from creating the cache held by Route 128, the Research Triangle, or Silicon Valley.

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Actors outside the core triple helix play passive roles in the innovation process. Consumers are marketed to and provide product feedback. Yet, there is little understanding of how else to engage them:

> "[Consumers] are important, but how do you really get them involved? I honestly don't think it is worth the effort." (Consulting Firms / Legal & Business; no. 2)

Non-profit advocacy organizations, including labor unions and environmental groups remain widely unrecognized in the innovation process (Table 4). The promoters of nanotechnology feel that those opposed to technology should not be part of the innovation process, as they get in the way. This sentiment aligns with the governance regime of 'techno-scientific promise' [40].

5. Discussion

Results show that actors follow preconceived mental models of innovation and governance (e.g. technology-push, market-oriented, technology-transfer, and closed-collaboration). Two models of government-initiated research illustrate contrasting approaches to nanotechnology innovation. The practice of technology-first investments by federal, state and even city agencies reinforces a technology-push innovation model. All the while, problem-based innovation (closed collaboration) for national defense is attempting to address the societal challenges involving safety and security. High yield market returns are driving market-oriented technology pull in the semi-conductor sector. All the while, advances in renewable energy, innovated via technology transfer out of university laboratories, are constrained by a lack of integration with infrastructures, legal and economic forces and by a lack of carbon accounting in the market. Currently, nanotechnology is thought of and practiced in a closed manner that is alternatively market-based, technology transfer-oriented, technology-push (linear) or through closed collaboration. No narratives depicted more open typologies of innovation, such as, social entrepreneurship, do-it-yourself or open source innovation.

Table 4
Actors considered important in the actor network of nanotechnology innovation in Phoenix (actor type, frequency of mentions, percentage of mentions).

Important actors	Number of mentions (45 interviewees)	Percentage of mentions (1202 mentions overall)
Industry	342	28.4%
Government agencies, federal	231	19.2%
Federal, funding	168	13.9%
Federal, non-funding	63	5.3%
Academia	231	19.2%
Private investment groups	111	9.2%
Consulting firms, business & legal	109	9.1%
Government agencies, urban	93	7.7%
Citizens & consumers	60	5.0%
Media	16	1.3%
Non-business advocacy organizations	9	<1%
Total	1202	100%

Furthermore, the city functions as a powerful organizing mechanism for nanotechnology activities in the first three phases of innovation and then the city's influence diminish thereafter. The dominant actor groups are academic, industrial, and government funding agencies (triple helix), with looser ties to other actor groups, including media and the public. The actor network is organized around activities including, funding, researching, and creating manufactured nanotechnology products. Yet, it is divided along product-based sectors with few cross-sector linkages. The dominant objective of innovation is to deploy profitable commercial or operational (military) products. Considerable governmental support for entrepreneurial (e.g. small business innovation research grants) and academic research through the National Nanotechnology Initiative is enabling the early phases of nanotechnology innovation. Yet, market failures (e.g. high cost manufactured nanoproducts) and corporate barriers (e.g. systematized production lines) are constraining the value proposition of nanotechnology in later phases.

This study set out to reveal key features of the current nanotechnology innovation process and governance regime in metropolitan Phoenix. The ultimate goal of the study is to contribute to the transformation of this regime to make sure that nanotechnology innovation happens in (more) anticipatory and responsible ways. To this end, we discuss the following flaws of the current regime and potential intervention points for transformation, based on the study results and novel technology governance concepts [37,58–61]; hereby, we draw in particular from the concept of anticipatory governance [10,62].

Stakeholders innovating nanotechnology leverage place-based resources such as the abundant solar radiation, the aging retiree population, the nanotechnology research community, and historical success in semi-conductors to generate profits, create employment opportunities, and deliver nanotechnology applications that outmatch other products and services. The innovation process is also uniquely challenged in Phoenix as it copes with, for instance, the cultural memory of land development; the belief that regulations are a burden to business; and fierce inter-city competition. While our study identified particularities to the place (Phoenix) and the type of technology (nanotechnology), the general structure of the nanotechnology innovation process in metropolitan Phoenix follows, in many respects, known patterns of technology development, including linear innovation. There is novelty in the products' functionality, but there is little evidence that nanotechnology in Phoenix currently offers novelty in its innovation process. Illustrated with our case study, we identify the following four critical features that pose challenges to the development of emerging technologies in general, and nanotechnology in Phoenix in particular [10,62].

5.1. Lack of integration

The actor network is divided along product-based sectors with few cross-sector linkages. Actors belonging to the same sector often describe collaborative activities

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supported by evidence, including joint proposals, grants, laboratory results, patents, publications, and entrepreneurial endeavors. Actors within the same sector are often considered (potential) collaborators; actors outside the specific sector, however, seldom engaged in innovation activities. Yet, even within the same sector, a lack of 'up- or down-stream' collaboration can be observed.

> "There are actually clinical trial companies here in Phoenix, they call me all the time. [...] I never pay any attention, because that is up-stream from where I am at, I always pass them along to those up-stream from me." (Industry; no. 6)

Opportunities for 'knowledge spillover' that cities foster inherently [63] are diminished by this lack of integration. Collaboration across sectors is seen as means to mutual learning, network robustness, accelerated innovation, cradle-to-cradle design, as well as to anticipating and mitigating negative social and environmental impacts [9,11,37,62,64]. The lack of 'up- or down-stream' collaboration is further discussed below.

5.2. Lack of anticipation

The innovation process does not account for unintended consequences that might negatively impact society or the environment in the future. Previous studies on nanotechnology application point to foreseeable negative impacts, such as, ethical controversy, pollution, worker accidents, and consumer safety issues [10]. The moratorium on new regulation is intended to remove unnecessary bureaucratic burdens, fostering laissez faire capitalism in Arizona. This differs from California's recent call-ins for selected nanomaterials [65] and from the national norm to allow state agencies to retain rule-making authority to protect public goods and interests. Suppressing rulemaking authority lessens the government's activity in anticipating threats and protecting workers, consumers, and the environment, which is in stark contrast to principles of sustainability-oriented governance [37,64]. Anticipatory governance promoting foresight, integration, and participation would be an advantageous approach to innovate emerging technologies such as nanotechnology in Phoenix.

> "The biggest challenge in the technology today, is not what is the biggest win, but what is the biggest unintended consequence in the technology or what is the unintended win. [...] In Arizona, you have to maintain all your wastewater within your municipal boundaries. Where [in other places] it is sent away, it goes away – you dilute into a river, you dilute into an ocean eventually that is going to have ramifications for the entire world. In Arizona it has ramification on a much quicker level. Eventually that [nanoparticle] is going to build up in your [groundwater] recharge, eventually that doesn't go away. We don't have enough studies to show how fast it goes away. [The city government] could be brought into it sooner in some of these advanced technologies that have societal implications, in the future or not. If they are brought in as part of that collaborative group, we can circumvent some of the problems that mankind will create themselves." (Government funding agencies; no. 4)

5.3. Lack of public participation & civic engagement

The current regime does not allow for public engagement opportunities at early stages of the process (up-stream, mid-stream). In fact, it does not even recognize the importance of consumers (or public opinion communicated through media outlets). There is little evidence in this study that 'the user matters' criterion is being addressed [61]. Public engagement is becoming a mechanism to create transparency and accountability in science and technology policy [66]. For example, California takes a proactive approach by conducting public workshops on nanotechnology development [65]. In metropolitan Phoenix, there would be ample opportunity for 'upstream' public participation as many local innovation actors are engaged in the first three phases of innovation. This would allow the public to shape the research agenda, identifying place-based problems, and providing early feedback on application concepts and prototypes. Our study, however, indicates strong resistance and inertia, as articulated by one workshop participant.

> "[Consumers] are important, but how do you really get them involved? I honestly don't think it is worth the effort." (Consulting Firms / Legal & Business; no. 2)

5.4. Lack of creating public value

The actor network myopically focuses on commercialization as the sole mechanism to bring value to the public. Value relies on market forces to maximize consumer utility and commercialization is the clear mechanism to realize the "economics of technoscientific promise" [40,62]. The underlying assumption is that economic growth through private markets will maximize utility (benefits) for citizens and maximize profits for corporations. It is assumed that profits will be reinvested and contribute to future growth. However, there is ample evidence that market-based commercialization creates negative externalities in the form of social and environmental externalities, which are not addressed in these assumptions [67]. In fact, externalities stemming from status quo commercial markets are part of the nanotechnology product portfolio [68,69].

6. Conclusions

While innovation studies often seek to contribute to the continuation of technological innovation in a sector or a region (e.g. Etzkowitz [70]), this study aspires toward a different outcome. The ultimate objective of this study is not continuation but transformation. There is novelty in the products' functionality, ranging from solar technology to personalized medicine, but there is little evidence that nanotechnology in Phoenix offers novelty in its innovation and governance process. Actors, almost exclusively, follow preconceived mental models of innovation and governance (e.g. market-oriented or closed-collaboration). Little attention is paid to adverse effects, co-construction, or broader public value generation. These characteristics stand in stark contrast to state-of-the-art governance for emerging technology development.

Phoenix in particular, displays some significant shortcoming with adverse effects occurring over the long term, the present study aims at identify promising intervention points to transform existing governance regimes. Guiding concepts for this transformation are emerging in the concepts of sustainable and anticipatory governance (responsible innovation). The practice-oriented analytical perspective adopted in this study refers to the obvious fact that nanotechnology innovation happens through people, their decisions and actions. They act in real time and largely within a locally defined and bound network; hence, we focused on a metropolitan area. If innovation ought to happen somewhat differently (with somewhat different decisions and actions), namely in more anticipatory and responsible ways, we need to know who is doing what (and why) along the innovation process. Our study allowed practitioners to express their understanding of nanotechnology innovation and created an inventory of the current regime for the metropolitan area of Phoenix. This also provides initial hints towards flaws and potential intervention points.

Future research is needed in four areas. First, a criteria-based assessment is required to detail and substantiate the flaws in the current nanotechnology innovation process and governance regime. Such an assessment would need to be based on a synthesis review of current normative governance concepts to provide a transparent and substantive assessment base [37,60]. Second, a systematic participatory exploration is needed on which of the analyzed actors, activities, etc. along the innovation process would be conducive to introducing good governance practices, techniques for anticipation, sustainability principles, and so forth. For example, federal funding agencies are drafting and distributing RFPs, reviewing, approving and rejecting proposals, etc., and thus, they significantly shape nanotechnology innovation in a particular way. Considering current increase of sustainability-oriented programs and initiatives in federal research funding agencies (NSF, EPA, NIH), it seems to become a promising intervention point that government agencies would do these activities differently; e.g. including other guidelines in the RFPs; apply different criteria in the review process; do extended reviews (with stakeholder involvement); etc. Third, transformational research is needed that engages innovation actors in their environments (through participant observation and engagement) suggesting and exploring such alternative action schemes [71]. Fourth and final, comparable studies are needed to overcome the limitations of a single case study on metropolitan Phoenix and to tease out generic insights in all three streams, i.e. analyzing, assessing, and transforming the current innovation processes and governance regimes.

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