NANOMANUFACTURING OUTSIDE OF THE LAB:
AN ACADEMIC-INDUSTRY PARTNERSHIP CASE STUDY

by

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DEDICATION

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ABSTRACT

In 2003, policy entrepreneur Dr. Mihail Roco wrote in Nature Biotechnology, “The key goals of nanotechnology are advances in molecular medicine, increased working productivity, extension of the limits of sustainable development and increased human potential.” From initial visions like Roco’s until now, there has been significant investment and research progress in the field of nanotechnology. According to the White House, over $20 billion has been invested in nanotechnology research and development by the United States government since 2000.¹ There is now a growing emphasis on transitioning from a focus on fundamental research towards a focus on overcoming the barriers preventing technologies from being successfully integrated into devices manufactured at an industrial scale. The Woodrow Wilson International Center for Scholars’ Project on Emerging Nanotechnology maintains an index of consumer products reported to contain nanotechnology, which has over 1,800 entries.² However, compared with the pictures of “nano-futures” painted by early nanotechnology proponents, there are far fewer products than we might expect, and with much less life-altering outcomes than some predicted.

While much focus has been placed on the technical barriers to commercialization, barriers outside of the lab must also be addressed in order to achieve broader adoption of nanotechnology. These barriers may include public awareness and acceptance, regulation, and issues with technology transfer. A structure that can have significant impacts on the commercialization of nanotechnologies is the academic-industry partnership. Such
partnerships are a delicate dance of communication, intellectual property, and shared resources that have the potential to greatly accelerate research progress and commercialization, but can also stop such progress in its tracks if they do not work out.

A case study has been conducted of an active research partnership between Boise State University and Micron Technology. Together, these partners are examining the use of DNA nanostructures in semiconductor memory manufacturing. This study seeks to gain insight into the roles that policy and cultural barriers play in the commercialization of an emerging nanotechnology developed through this unique partnership.

This case study used coded qualitative interviews to collect perspectives on the challenges and opportunities of university-industry partnerships and of scaling nanotechnology in manufacturing. Groups interviewed included researchers on the project under study, as well as administrators associated with the project or other similar projects that involve collaborations between academia and industry.

From these interviews, insight is drawn into the challenges and opportunities of such collaborations, relative to nanotechnology and other emerging technologies that may be developed through academic-industry partnerships. Recommendations are presented, based on interview findings and relevant literature that seek to inform future collaborations between academia and industry and improve outcomes from such partnerships, both for the collaborators and society at large.
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<table>
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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ASU</td>
<td>Arizona State University</td>
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<tr>
<td>Boise State</td>
<td>Boise State University</td>
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<td>CNS</td>
<td>Center for Nanotechnology and Society</td>
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<td>CO</td>
<td>Carbon Monoxide</td>
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<td>CVD</td>
<td>Chemical Vapor Deposition</td>
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<td>DNA</td>
<td>Deoxyribonucleic Acid</td>
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<tr>
<td>DSA</td>
<td>Directed Self-Assembly</td>
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<tr>
<td>EHS</td>
<td>Environmental Health and Safety</td>
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<tr>
<td>FMEA</td>
<td>Failure Mode Effects Analysis</td>
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<tr>
<td>GMO</td>
<td>Genetically Modified Organism</td>
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<tr>
<td>I/U-CRC</td>
<td>Industry/University Cooperative Research Centers</td>
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<td>IC</td>
<td>Integrated Circuit</td>
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<td>IWGN</td>
<td>Interagency Working Group on Nanotechnology</td>
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<td>LNA</td>
<td>Locked Nucleic Aid</td>
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<td>Micron</td>
<td>Micron Technology</td>
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<td>NAM</td>
<td>Nucleic Acid Memory</td>
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<td>NIH</td>
<td>National Institutes of Health</td>
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<td>NISE</td>
<td>Nanoscale Informal Science Education Network</td>
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<td>nm</td>
<td>Nanometer</td>
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<td>NMDG</td>
<td>Nanoscale Materials and Device Group</td>
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<tr>
<td>Acronym</td>
<td>Full Form</td>
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<td>---------</td>
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<td>NNI</td>
<td>National Nanotechnology Initiative</td>
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<td>NRC</td>
<td>National Research Council</td>
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<tr>
<td>NSF</td>
<td>National Science Foundation (United States)</td>
</tr>
<tr>
<td>PI</td>
<td>Principle Investigator</td>
</tr>
<tr>
<td>PVD</td>
<td>Physical Vapor Deposition</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
</tr>
<tr>
<td>RNA</td>
<td>Ribonucleic Acid</td>
</tr>
<tr>
<td>SNM</td>
<td>Scalable Nanomanufacturing Project (specifically, the project at Boise State funded under the grant, “Atomically Precise, Defect Free, DNA Masks with Embedded Metrology”)</td>
</tr>
<tr>
<td>SRC</td>
<td>Semiconductor Research Corporation</td>
</tr>
<tr>
<td>STM</td>
<td>Scanning Tunneling Microscope</td>
</tr>
<tr>
<td>TTO</td>
<td>Technology Transfer Office</td>
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<tr>
<td>US</td>
<td>United States of America</td>
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CHAPTER ONE: INTRODUCTION

Since President Bill Clinton introduced the National Nanotechnology Initiative (NNI) in the year 2000, over $22 billion have been invested by the US federal government (including requested funds in President Obama’s 2016 budget) to fund nanotechnology research and development. Nanotechnology has shown great potential in a wide variety of applications, many of which are expected to be integrated into products. Nanoparticles are already found in products such as sunscreens, and the global nanotechnology market has been forecasted to be valued at $4.4 billion by 2018.

However, compared with the expectations that many had at the outset of the NNI, relatively few nanotechnologies have reached the market (around 1,800, according to the Project on Emerging Nanotechnologies).

The semiconductor industry may be considered a notable exception to this lack of widespread commercialization. However, the work of the semiconductor industry is not commonly thought of as nanotechnology. This is surprising, since common semiconductor products, such as flash memory and computer processors, now include many nanoscale features. Much of this research has been developed or funded, at least in part, by semiconductor companies or through the Semiconductor Research Corporation (SRC), which is a consortium of semiconductor companies that supports pre-competitive research with financial support from DARPA.

Obstacles to the development of nanotechnologies can appear in a variety of forms, including regulations, public acceptance, and difficulties with technology transfer.
The report on a 2013 summit convened by the US Government Accountability Office included a list of challenges to US leadership in nanomanufacturing, which included gaps in funding for nanotechnology commercialization (sometimes referred to as the “Valley of Death”) and limited technology transfer capabilities at US universities.\(^6\)

University research labs play a significant role in discovering and researching new nanotechnologies. However, universities are not in the business of manufacturing products, so these technologies need to break out of the university lab and into industry in order to become products. Breaking out can happen through a variety of channels, including partnerships between universities and industry, technology transfer through patenting and licensing, and academic entrepreneurship, where university faculty or students spin off a company from a university lab. Knowledge can also be transferred out of a university through formal and informal connections and collaborations with industry.\(^7\)

While these factors have been studied individually, there has not yet been a significant amount of scholarly work devoted to academic-industry partnerships and how they relate to the commercialization of nanotechnologies. This thesis seeks to contribute to an understanding of these issues through the study of a collaborative nanotechnology research project being led by Boise State University.

In the spring of 2014, the National Science Foundation (NSF) awarded a grant to researchers at Boise State University, Harvard University, and Micron Technology for a proposal submitted to the Scalable Nanomanufacturing program, entitled “Atomically Precise, Defect Free, DNA Masks with Embedded Metrology”.\(^8\) This grant proposed to address scaling challenges for the semiconductor industry to “enable high-volume
manufacturing of atomically-precise, defect-free patterns made from synthetic DNA” and “self-report defects using an in-line optical technique to monitor the quality control of patterns during high-volume production”. In addition to these technical goals, the project also included funding for a social science study of the project to review the relevant literature and conduct a case study of the project to generate recommendations for public-private collaborations in scalable nanomanufacturing.

While the Wyss Institute at Harvard University is a part of the SNM project, they did not collaborate directly with Micron as a part of this project. Thus, consistent with a focus on academic-industry partnerships, this case study focuses solely on the relationship between Boise State University and Micron Technology.

This thesis will present research from this social science study, along with relevant technical background information. The research questions that this thesis seeks to answer are: Has the academic-industry partnership in this project been beneficial to any or all parties involved? How does this project compare to what has been written in the literature about such collaborations? What lessons can be learned from this project that can be applied to other projects?

Chapter 2 gives background information to provide context for the following research. This includes general information about the technical details of nanotechnology, the effect of the nanoscale on physical properties, and an overview of details relevant to the SNM project, including photolithography and DNA nanotechnology. This chapter also provides background information on the policy history of nanotechnology in the United States, an overview of some of the social science
literature that has been published regarding nanotechnology, and a brief description of the technology transfer process at universities.

Chapter 3 describes the results of a quantitative literature review of social science articles regarding nanotechnology, focused on finding articles that could be relevant to nanomanufacturing, especially from the perspective of a nanomanufacturing practitioner such as a researcher in a university laboratory or in industry.

Chapter 4 describes the methodology used in the case study of the SNM project, including the interview method, research questions, selection of interviewee population and data analysis strategy. Chapter 5 describes the results of the interviews, including answers to research questions and common topics discussed. This chapter concludes with interviewees’ lessons and suggestions for academic-industry partnerships. Chapter 6 provides a summary of the thesis and asserts some recommendations for future projects of this nature.
CHAPTER TWO: BACKGROUND

Due to the interdisciplinary nature of this research, background is required from a wide variety of subjects surrounding nanotechnology and the SNM project, both technical and non-technical. On the materials side, the technical details of nanotechnology and the implications of the nanoscale are explored, and the field of DNA nanotechnology is introduced. Concepts related to the goals of the SNM project are also introduced – most notably, photolithography, and the limitations of that technique.

From the policy side, a brief history of nanotechnology policy in the United States is provided, as well as some of the non-technical challenges that proponents of nanotechnology have faced in advancing the field. A brief overview of social science literature relevant to nanotechnology is provided. Finally, some of the factors involved in bringing new nanotechnologies into products are discussed – technology transfer, commercialization, relevant legislation and, the main focus of this thesis, academic-industry partnerships.

Nanotechnology

According to the 2014 NNI Strategic Plan, “Nanotechnology is the understanding and control of matter at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications.” One nanometer is one billionth of a meter (or $1 \times 10^{-9}$ m), and a common convention is that something exists on the nanoscale when it has at least one feature within this 1-100 nanometer (nm) range. Due to the nature of physics at this scale, often involving surface-dominant phenomena, materials and
particles with features on the nanoscale can exhibit significantly different properties from their macro-scale counterparts. For instance, macro-scale objects made of gold are yellow in color, while colloidal solutions of gold nanoparticles can appear a dark red color.\textsuperscript{10}

The concept of nanotechnology is generally considered to originate from a speech entitled “There’s Plenty of Room at the Bottom”, which was given by Richard Feynman at annual meeting of the American Physical Society at the California Institute of Technology in 1959\textsuperscript{11}, though others have suggested that these ideas were presented prior to this talk in science fiction stories, such as Robert Heinlein’s “Waldo”, which was published in 1942\textsuperscript{12}. Regardless of who came up with the initial ideas that spawned the field of nanotechnology, K. Eric Drexler is widely credited with bringing nanotechnology to the masses, beginning with his book, \textit{Engines of Creation}, which was published in 1986.\textsuperscript{13,14} In the book, Drexler described “assemblers” – factories shrunk to the nanoscale which could self-replicate and build almost anything.\textsuperscript{13} While the scientific soundness of Drexler’s visions has been questioned by many, including prominently by Dr. Richard Smalley\textsuperscript{15}, there is no doubt that his writings played a role in increasing public awareness of nanotechnology. The term, “nanotechnology” was coined by Norio Taniguchi in his 1974 paper “On the Basic Concept of ‘Nano-Technology’”.\textsuperscript{16}

\textbf{Policy History of Nanotechnology}

In the approximately 10 years that nanotechnology was a prominent item on the US government research agenda (from 2000-2010), there were two major increases in focus on the subject. This is reflected in the number of nanotechnology entries in the Congressional Record, as seen in Figure 2.1.
The first increase in prominence coincided with the enactment of the NNI in 2001, and was characterized by widespread optimism about the benefits that nanotechnology could bring for society, and the conviction that the US needed to be the R&D leader of nanotechnology worldwide. In 2003, the US Congress passed the 21st Century Nanotechnology Research and Development Act, which affirmed and expanded the federal government’s role in funding nanotechnology research and development. This period ended around 2004.

Figure 2.1: Number of Nanotechnology Entries in the Congressional Record, 1997-2014, from a Search for the Term “nanotechnology” on ProQuest Congressional. Figure duplicated from Anticipatory Policymaking: When Government Acts to Prevent Problems and Why It Is So Difficult by Rob A. DeLeo, page 46.14

The second round of policy activity occurred between 2007 and 2010, and was much more focused on the potential risks of nanotechnology, and calls for increased funding of research on health and safety issues around nanotechnology. While the
federal government still funds nanotechnology R&D (President Obama’s 2016 Budget included $1.5 billion for the NNI), in recent years, nanotechnology has not been as prominent of a policy issue as it was during this period.

The history of nanotechnology policy in the United States begins largely with Dr. Mihail Roco, a mechanical engineer working at the National Science Foundation. With the stage set for public awareness of nanotechnology by Eric Drexler, Roco was the most prominent policy entrepreneur that drove the creation of nanotechnology policy within the United States government, both within the executive branch and through Congress. Policy entrepreneurs are defined by Kingdon as “advocates for proposals or for the prominence of an idea”.17 Policy entrepreneurs invest their own time and resources (and sometimes their reputations) in hopes of a future return, in the form of policies which benefit them and/or their interests.17 In Roco’s case, in 1997, he was instrumental in the founding of the Interagency Working Group on Nanoscience, Engineering, and Technology (IWGN).14 This group reported to the National Science and Technology Council, a Cabinet-level council which coordinates science and technology policy for the executive branch, which was established by an executive order from President Clinton in 1993.18

The IWGN’s vision for a multi-agency push for nanotechnology research and development was called the “National Nanotechnology Initiative” (NNI). Roco pitched this idea to White House advisors in 1999, and personally educated members of congress about the anticipated benefits of nanotechnology.14 In January 2000, President Clinton gave a speech at the California Institute of Technology where he detailed his vision for the role of the federal government in nanotechnology.19
This announcement was followed by a budget request for almost $495 million in funding for the NNI and nanotechnology research and development. There was a large amount of optimism at this time from prominent scientists, politicians and science enthusiasts about the promise of nanotechnology, and the technology was largely cast in a positive light, as a technology with great potential to do good for society. While the Clinton administration put forward the NNI, support was bipartisan, with Newt Gingrich, former Republican House Speaker from Georgia, calling the NNI in 2002 “one of the better things the government has done.”

Underscoring this, nanotechnology was widely characterized as having the potential to bring about “the next Industrial Revolution”. Other dominant narratives at this time were of economic and national security and the importance of the US becoming the global leader of this new technology.

Nanotechnology was presented as a solution to a wide variety of problems during this time, especially as it became evident that nanotechnology could become a significant source of research funding. With so many interests, both public and private, involved with and competing for nanotechnology funding, many different definitions of nanotechnology were put forth from different sources, such as the US National Research Council (NRC), the National Institutes of Health (NIH), and the National Science Foundation (NSF). Those concerned about the risks of nanotechnology also put forth their own definitions. Nanotechnology was cited as a potential solution for issues of national security, energy, the economy, and human health, among other areas.

However, this narrative was not as convincing to some people outside of Washington D.C., and soon this optimistic narrative was contrasted with another of
potential risks, both to the environment, as well as to vulnerable populations across the globe. While the Industrial Revolution led to many technological advances and an improvement in the standard of living of many people, especially in Western countries, this narrative was questioned by some who raised the question of what upheaval a potential nanotechnology revolution might bring.\textsuperscript{14}

Other voices painted much grimmer pictures than Drexler’s of out-of-control self-replicating nanomachines destroying the environment and endangering humans. Bill Joy, co-founder of Sun Microsystems, wrote in an article in \textit{Wired} magazine about the “grey goo threat”, where uncontrolled self-replicating nano-“bacteria” could spread and “reduce the biosphere to dust in a matter of days.”\textsuperscript{22} Michael Crichton’s 2002 science fiction thriller, “Prey”, depicted a group of scientists trapped and hunted by a deadly swarm of predatory self-replicating nanoparticles.\textsuperscript{23}

A second narrative used by opponents of nanotechnology was a comparison to another emerging technology that had been surrounded by considerable controversy - Genetically Modified Organisms (GMO’s). GMO’s are organisms whose genetic material has been altered through the use of genetic engineering techniques. Such techniques provide the ability to modify the traits of an organism, sometimes through the introduction of genetic material from another organism. Perhaps the highest-visibility application of GMO’s is in agriculture, where crops have been modified to increase their resistance to pests (or pesticides), their shelf-life, and their nutritional value. While some of these crops, such as “Golden Rice” (a rice genetically modified to produce beta-carotene, an important nutrient for eyesight\textsuperscript{24,25}) were developed with the intention of helping people, the use of GMO’s in agriculture by companies such as Monsanto has
drawn significant backlash. Some saw the potential for the manipulation of materials via nanotechnology as comparable to the manipulation of genes in GMO’s, with the potential for unforeseen (and potentially dangerous) consequences.

GMO opponents weren’t the only ones to see a parallel between nanotechnology and GMO’s. The backlash against GMO’s in the late 1990s was partially directed at policymakers, who were seen as considering the needs of industry over those of the public in introducing a new technology without considering the concerns of the public. While few nanotechnology opponents called for an outright ban on the technology, many called for measures to be put in place proactively to identify the potential dangers of nanotechnology products before they entered the market.

One provision of the 21st Century Nanotechnology Research and Development Act addressed concerns about the future impacts of nanotechnology by mandating that the newly established National Nanotechnology Coordination Office ensure “that ethical, legal, environmental, and other appropriate societal concerns... are considered during the development of nanotechnology...” This consideration was to take place through the support and dissemination of research exploring ethical, legal, environmental, and other societal concerns around nanotechnology, as well as through integrating this research with technical nanotechnology research as much as possible and “ensuring that advances in nanotechnology bring about improvements in quality of life for all Americans.”

Two Centers for Nanotechnology in Society (CNS) were established at Arizona State University (ASU) and University of California, Santa Barbara in 2005, with other projects related to nanotechnology in society also funded at Harvard University and the University of South Carolina. Researchers at CNS ASU investigated a number of
anticipatory policy approaches to examining the future implications of nanotechnology, including engaging researchers through “real time technology assessment” with embedded social scientists and humanists, as well as visioning and public engagement efforts such as the Nanoscale Science Informal Education (NISE) Network which engaged science museums to become centers of public deliberation about nanotechnology.30

Social Science Literature on Nanotechnology

Through the work of the Centers for Nanotechnology, as well as other research groups focused on the study of the ethical, legal, and societal impacts of nanotechnology, a considerable body of social science scholarship has emerged addressing the development, research output, and impact of the field of nanotechnology.

Shapira, Youtie, and Porter published a study in 2010 of social science literature on nanotechnology.31 Their hypothesis was that social scientists writing about nanotechnology would initially look to technical literature, and then later, as the technology developed, would begin to draw more on the work of other social scientists. Their method of analysis was examining how papers cite each other, and in order to do this, they created a database of social science literature on nanotechnology.

Shapira et al. found that the articles they examined fell into 16 top categories, each containing more than ten publications in their sample of 308 articles, related to the subject matter addressed in the articles. It is worth noting here that, though the bulk of this thesis focuses on the case of nanotechnology in the United States, Shapira et al’s sample included articles from 11 countries. These subject categories listed are as following, from most to least articles.31
Chapter 3 of this thesis describes a similar, updated literature review that focused on identifying articles relevant to nanomanufacturing.

Nanoscale Properties

The nanoscale is very close to the scale of atoms and molecules. For instance, the bond length between two carbon atoms in diamond is 154 pm (or 0.154 nm), putting the covalent radius of carbon at 77 pm (or 0.077 nm)\textsuperscript{32}. Thus, nanotechnology involves the potential of manipulating individual atoms. This has been a subject of excitement for many nanotechnology futurists, including Richard Feynman, who referenced the idea of
writing by arranging atoms in his 1959 talk\textsuperscript{11}. This can already be done using techniques such as Scanning Tunneling Microscopy (STM).\textsuperscript{33}

The nanoscale affects properties in a variety of ways, and can in some cases even affect intrinsic properties, such as resistivity, which are generally considered to be uniform throughout a sample. Nanoparticles have a high surface-to-volume ratio, which can lead to significant changes in reactivity, compared with their bulk counterparts. Surface atoms are naturally more reactive, since they have fewer neighboring atoms to bond with. In nanostructures, since so much of the structure is on the surface, a higher proportion of atoms are in this state of increased reactivity. In terms of electronic structure, the energy required to remove electrons from nanostructures (ionization energy) is also generally higher than for the corresponding bulk materials.\textsuperscript{10} The interatomic spacing and crystal structure of nanomaterials (especially nanoparticles) can be different from bulk properties of the same material. In nanoparticles, this is explained by the compressive strain of internal pressure caused by the small radius of curvature of the particle. These differences can lead to changes in thermal properties, such as melting points. Nanostructures can also exhibit impressive mechanical properties, often due to the lack of room for defects to form and move through the small dimensions of the materials.\textsuperscript{10} Multi-walled carbon nanotubes have been shown to exhibit tensile strengths of 11-63 gigapascals\textsuperscript{34}.

Since the nanoscale is so close to that of atoms themselves, electronic properties can change due to the higher prevalence of the wave-nature of electrons at this scale. Differences in electronic properties can also contribute to differences in optical properties, especially those related to valence and conduction bands. Semiconductor
nanocrystals (often referred to as “quantum dots”) exhibit size-dependent optical behavior related to the frequency and intensity of light emitted by them after excitation. These property differences from corresponding bulk materials open exciting possibilities for new applications. However, they also pose regulatory challenges, as lawmakers must determine how to regulate materials that are elementally the same, but whose properties vary drastically based on size.

Manufacturing at the Nanoscale

Most of the objects that we interact with in day-to-day life (chairs, staplers, etc. -- we will call this the macro-scale) are made using manufacturing processes such as molding, casting, and machining. Some of these processes are also somewhat applicable on the nanoscale. So-called “top-down” manufacturing processes, such as photolithography (discussed in more detail later in this chapter) are used to form nanoscale structures in similar ways as the macro-scale approaches listed above, by removing material from a larger structure to make it smaller, until its features reach a nanometer scale. While methods such as photolithography are used widely in industry, they have inherent limits that can make reliably achieving precise features difficult on the scale of several nanometers using the current tools that are widely used in industry. This technique also has the limitation that it only works on very flat surfaces, such as polished silicon wafers.

One answer to these challenges is the idea of “bottom-up” assembly. Small building blocks of matter can be manually manipulated on the nanoscale through techniques such as Scanning Tunneling Microscopy (STM), as demonstrated by IBM researchers in the stop-motion animated film, “A Boy and His Atom”, which was
animated by moving carbon monoxide (CO) molecules around a copper plate using an STM. However, such processes are laborious and not currently scalable for large-scale manufacturing. Chemical and Physical Vapor Deposition (CVD and PVD, respectively, as well as Molecular Beam Epitaxy, can create thin films of materials, or structures such as fullerenes or carbon nanotubes. However, vapor deposition processes have some drawbacks when it comes to controlling the formation of three-dimensional structures such as carbon nanotubes. Thus, the idea of nanoscale building blocks that assemble themselves is very attractive, especially to the semiconductor industry, which is searching for methods that can extend the resolution of photolithography. Two technologies that have been put forth to address this are block copolymers and DNA, which will be discussed further in the next section.

**SNM Project Background**

In 1965, Gordon Moore, co-founder of Intel, put forth what is now known as “Moore’s Law” – a prediction that the density of transistors in an integrated circuit (IC) would grow exponentially over time. As the drive for miniaturization pushes the semiconductor industry close to the limits of their current technologies, research into new technologies seeks to overcome these barriers. The SNM Project proposes several novel approaches to solving one of the most important challenges limiting the continuation of Moore’s law – the limitations of photolithography.

**Photolithography in Semiconductor Manufacturing**

Photolithography is a technique used to create precise patterns on silicon wafers. It is one stage in the process of creating the complex multi-layer circuits and structures that make up today’s semiconductor memory and computer chips (see Figure 2.2).
Figure 2.2: The process of manufacturing semiconductor devices. This figure illustrates the steps required to manufacture a semiconductor IC, as well as where photolithography fits in this process. Figure duplicated from *Manufacturing Techniques for Microfabrication and Nanotechnology* by Marc J. Madou, page 3.37

An example of the basic steps in a photolithography process can be seen in Figure 2.3. A thin layer of photosensitive polymer, called a photoresist, is applied to the surface of a silicon wafer (see Figure 2.3.a). This layer is then exposed to light of a specific wavelength, which is projected through a patterned mask onto the wafer surface (Figure 2.3.b). The image formed on the photoresist layer by the light is then developed, selectively hardening the photoresist material in a pattern, which corresponds to the desired features to be patterned on the underlying wafer (Figure 2.3.c). This leaves some areas of the wafer surface protected from subsequent steps in the process, such as etching or ion implantation. Figures 2.3.d to 2.3.f depict a process in which the photoresist has selectively protected areas of a layer of silicon dioxide, which is then etched away in some areas, revealing the wafer surface underneath, which is then able to be etched to form features.
Figure 2.3: Example Photolithography process (cross-sectional view)

Limits of Photolithography Resolution

Photolithography techniques are limited by the diffraction limit of light - in this case, of the wavelength of light shone through a mask. The definition of features formed on the photosensitive mask layer is partially dependent on and limited by the wavelength of the light used to set the photoresist, as well as the thickness and intrinsic sensitivity of the resist. While the lithographic sensitivity of a resist to generate crisp images from light shone through a mask is best determined experimentally, Madou gives the following equation for the theoretical resolution of “shadow printing” through a mask (in the theoretical case, this mask is a grating):

\[ R = b_{\text{min}} = k \sqrt{\lambda \left( s + \frac{Z}{2} \right)} \]

where \( b_{\text{min}} \) is half the period of the grating (this is also the minimum feature size transferrable to the photoresist), \( s \) is the separation between the mask that the light is
shone through and the surface of the photoresist, $\lambda$ is the wavelength of the light shone through the mask, $z$ is the thickness of the photoresist, and $k$ is a constant (theoretically, this is approximately 1.5).\(^{37}\)

**Block Copolymers**

The 2012 International Technology Roadmap for Semiconductors included “directed self-assembly” (DSA) of block copolymers as an emerging material which was being evaluated for use in lithography.\(^{38}\) Researchers at Micron Technology have explored the use of block copolymers, in conjunction with features created using photolithography, to define smaller features lithographically.\(^{39}\) In block copolymers, two distinct types of polymer chains are covalently bound together. When the two types of polymers that are combined are also immiscible, phase separation will occur, causing the polymers to self-assemble into periodic structures.

While block copolymers may seem promising, challenges exist with the use of block copolymers for patterning which are difficult to overcome. Chief among these are defects in the self-assembled structures formed by the block copolymers that vary with the width of the lithographically defined trenches that the block copolymers are self-assembling between (see Figure 2.4). Figure 2.4.a shows defects that can occur in block copolymers that are self-assembled between patterned features that are too far apart.
Figure 2.4: Block Copolymer Defects (trenches in both images are ~10 nm wide). Images courtesy of Micron Technology, Inc.

Figure 2.4.b shows another type of defect that can occur in block copolymer systems, which is similar to a dislocation defect in a material. Since block copolymers assemble with no direction other than phase separation, controlling and eliminating these defects is difficult.\textsuperscript{39}

DNA Nanotechnology

DNA Nanotechnology is a sub-field of nanotechnology that focuses the use of deoxyribonucleic acids (DNA) and other nucleic acids, harnessing on their ability to programmably self-assemble. This feature, based largely on Watson-Crick base-pairing, makes DNA especially attractive for bottom-up self-assembly. By designing synthetic DNA with custom sequences, structures can be created to perform a variety of functions, including circuits, actuators, sensors, and scaffolds for the formation of other nanostructures.\textsuperscript{40}
Figure 2.5: Examples of Structural DNA Nanotechnology from Literature. Figure duplicated from *Structural DNA Nanotechnology: State of the Art and Future Perspective*, by Fei Zhang et al., Figure 1.
Figure 2.5 depicts some examples of DNA nanostructures, including Seeman’s original proposed four-way junctions (Fig 2.5.a)\textsuperscript{41} and DNA lattices (Fig 2.5.b)\textsuperscript{41}, repeating DNA motifs used to create two- and three-dimensional arrays with microscope images (Fig 2.5.c)\textsuperscript{42–45}, polyhedral DNA nanostructures (Fig 2.5.d)\textsuperscript{46–49}, and algorithmic self-assembly of crossover tiles (Fig 2.5.e)\textsuperscript{50,51}. Shown in this figure are also the two dominant methods of creating structures from DNA – Rothemund’s DNA origami (Figure 2.5.f)\textsuperscript{52–55} and the Yin group’s DNA bricks (Figure 2.5.g)\textsuperscript{56,57}.

DNA origami uses a long, single-stranded “scaffold” strand of DNA (commonly, this comes from the M13-mp18 E. coli bacteriophage), which is folded into a two- or three-dimensional shape by shorter single-stranded synthetic DNA strands, called “staple” strands. DNA origami is depicted in Figure 2.6, with the scaffold strand in black and the staple strands in color. Staple strand sequences are typically generated using a computer program, such as caDNAno.\textsuperscript{58,59} DNA bricks use a similar principle, except that there is no scaffold strand, so the entire structure is built out of “staple” strands. This enables the flexible creation of a wide range of two- and three-dimensional shapes (as seen in Figure 2.5.g) by selective exclusion of some of the strands.
Figure 2.6: Example DNA Origami Structure (scaffold shown in black and staples shown in color).

SNM Project Goals

The project described in the grant proposal funded under the title, “Atomically Precise, Defect Free, DNA Masks with Embedded Metrology”,\textsuperscript{8} contains several technical objectives. The first is to create a mask from DNA crystals that would be equivalent to existing masks formed from block copolymers and ideally free from defects.\textsuperscript{8} The second component is the precise placement and alignment of such DNA crystals onto areas on a silicon wafer defined using existing photolithography techniques, similar to work demonstrated by Kershner \textit{et al.}\textsuperscript{60} The use of the DNA PAINT technique (PAINT stands for “point accumulation for imaging in nanoscale topography”), which uses the transient binding of fluorescent dye molecules attached to single-stranded DNA to a structure,\textsuperscript{61} was proposed as the “embedded metrology” to detect defects in-situ.
during high-volume manufacturing. Lastly, it was proposed that once the DNA crystal mask had been assembled and tested, that the pattern from the mask would then be transferred to a hard lithographic mask.⁸

**Commercialization and Technology Transfer in the University Setting**

**Technology Transfer Process**

The traditional process of technology transfer at a university begins when a faculty, staff, or student identifies a discovery that they have made as having the potential for commercialization and reports it to the university Technology Transfer Office (TTO). This report, sometimes referred to as a “disclosure”, includes background information about the invention, as well as any organizations that the researcher knows of that might be interested in licensing the technology. Any potential barriers to patenting, such as previous publications, must also be included. The TTO then reviews this information and does research to determine the commercial potential and potential market for the technology, to determine whether it will be worth the university’s resources to invest in patenting the invention.⁶²

While this may seem like a fairly clear path to commercialization, Thursby *et al.* published a survey in 2001 in which TTO staff speculated that faculty at their institutions disclosed less than half of the potentially commercialize inventions discovered at their institutions. This survey also indicated that institutions allocated resources to pursuing patents only when they perceived an idea to be easily licensed.⁶³ This is likely attributable to limited university resources and the high cost to process a patent, which decreases the incentive for patenting without a clear path to a return on this investment through licensing.
While budget constraints still provide a barrier to patent applications for small and mid-sized institutions such as Boise State, it is possible that such approaches may have changed in recent years, since the passage of the *America Invents Act* in 2013, which changed the long-standing US “first-to-invent” system to a “first-to-file” system, more similar to that seen in other countries.\(^{64}\) While provisions of the act provide a one year “grace period” for inventors to make disclosures (such as conference presentations) about their inventions before filing for a patent, some have argued that the new system favors large businesses over smaller businesses, universities, and individual inventors.\(^ {64,65}\)

**Bayh-Dole Act**

Prior to 1980, inventions that came out of federally funded research in the United States were owned by the government, and would not be exclusively licensed to any one company or organization. This created a significant barrier to investment in licensing federally funded patents, as the first company that licensed the technology and invested in developing the invention for commercialization could easily be taken financial advantage of by subsequent companies who could license the same invention under the same terms, without having to invest in the idea as the first company had.\(^ {66}\)

The Bayh-Dole Act solved this issue by allowing institutions that generated inventions through federally funded research to own the inventions, and also to have the opportunity to exclusively license them to one licensee.\(^ {66,67}\)

**Academic Engagement**

Academic engagement is defined by Perkmann *et al.* as “*knowledge-related collaboration by academic researchers with non-academic organizations.*” Activities that fall within this definition include collaborative research, contract research and
consulting performed by academic researchers with entities outside the university, as well as less formal interactions such as networking. These sorts of relationships may sometimes be referred to as “informal technology transfer”, though many of them involve some sort of formal contract. They contrast these sorts of relationships with the more well-recognized concept of commercialization, which encompasses patenting and licensing technologies, as well as academic entrepreneurship, where professors and/or students start a company to commercialize an idea developed within the university.⁷

While commercialization is often considered the primary mode of technology transfer, and may be perceived by many to be the most lucrative, Perkmann et al. note that for most universities, the income from academic engagement activities far outweighs that from licensing revenues.⁷ Many companies also consider these sorts of interactions to be considerably more valuable than simply exchanging the use of an idea for money through licensing.⁶⁸
CHAPTER THREE: LITERATURE SURVEY

The following research was conducted to fulfill one of the stated goals of the social science component of the SNM grant proposal – to perform a meta-analysis of the current social science literature on nanotechnology to determine what of it, if any, could be relevant to nanomanufacturing “practitioners”, defined as research scientists in university labs or in industry.

**Literature Search Methodology**

To characterize non-technical literature on nanotechnology, we attempted to replicate a search similar to what we believe a nanotechnology or nanomanufacturing practitioner might perform if they were looking for articles pertaining to these subjects outside of their direct field of study. We searched the Web of Science Core Collection in the Social Science Citation Index and the Arts and Humanities Citation Index using the search term “nano*”, which returned articles containing words that begin with “nano”. No limit was provided for when articles were published. We further narrowed our search by excluding all but a few “Web of Science Categories”. The categories that we included were as follows:

- Social sciences biomedical
- History philosophy of science
- Ethics
- Public environmental occupational health
- Communication
- Humanities multidisciplinary
With these conditions, our search returned 664 articles. To further reduce the sample to a manageable size, articles were sorted from most-cited to least-cited according to Web of Science metrics. The intent of this ordering was to identify the most influential papers, which have attracted the attention of other authors in the field. We also thought that this might be a likely strategy employed by a nano practitioner looking for “top” articles in other fields. Articles that were clearly irrelevant to the desired subject matter (i.e. papers on second-hand smoke that used units of nanograms/milliliter) were culled by hand, and the remaining top 100 papers were selected as the study sample set. A list of the titles, authors, and publication information of these articles can be found in Appendix A.

Once the sample set was established, a set of codes were generated to categorize the papers for analysis. These categories were loosely based on those provided by Shapira et al. in their 2010 *Scientometrics* paper, to which we added some codes and removed others based on subjects observed in our sample set. Again, our intent was to identify subjects that might be of interest to nano practitioners, especially those involved with nanomanufacturing.

We added several codes to Shapira et al.’s original list, including one for articles addressing nanomanufacturing lab practices and applications (including Environmental Health and Safety, or EHS), one for articles where the stated audience or research subject
was lab workers or scientists working in nanotechnology, and one for articles concerned in large part with toxicology or risk assessment. These additional codes were specifically targeted toward subjects that we believe would be of direct interest to nanomanufacturing practitioners.

Several of Shapira et al.’s original codes were also excluded, combined, or expanded to make them more directly applicable to our dataset. “Evolutionary economics”, for instance, was excluded completely, as our dataset included no articles with economics as their primary focus. “Public perception and deliberation” was split into two codes – “Public perception and values” and “Deliberation and engagement”, to differentiate between articles concerned primarily with how deliberation experiments are conducted and their utility, versus those that focus on actual measurements of what the public perceives about nanotechnology. The final set of codes included:

- Predictions/Visions/Pop Culture
- Institutional Governance
- Public Perception and Values
- Deliberation and Engagement Experiments
- Ethics
- Media Studies
- Science Mapping
- Addresses nanomanufacturing lab practices and applications (including EHS)
- One stated audience or research subject is lab workers or scientists (in nanomanufacturing)
- Toxicology/Risk assessment
Articles were also coded based on the predominant topic of the paper. For example, an article that focused primarily on ethical considerations of nanotechnology would be coded under “Ethics”, whereas a toxicology paper that mentioned ethics briefly at the beginning would not be coded under “Ethics”. The top 20 articles were coded by both coders, then compared to ensure general agreement and to refine the code categories to better capture the subject matter seen in the articles in the dataset. The next 80 articles were divided into two parts (even and odd numbers, by citation rank) and divided between the two coders. Codes were clarified and changed as necessary during the coding process, and coding changes were implemented throughout the sample set by both coders.

After all articles in the dataset had been coded, the number of articles for each code was tabulated using Microsoft Excel. Articles were also profiled by year and by journal.

**Literature Search Results**

Even before looking at the distribution of articles within the codes, several observations may be made about the timeline on which the articles in our sample set were published. There is a clear peak visible in Figure 3.1 in the number of highly cited articles published around 2009. This likely corresponds with research that came out of early funding opportunities from the NNI, and from the two Centers for Nanotechnology in Society at Arizona State University and University of California, Santa Barbara.
Another observation about the sample set as a whole may be seen in Figure 3.2, regarding which journals are most represented within the reviewed articles. The most articles came from *Public Understanding of Science* (19), followed by *Science Communication* (12) and *Risk Analysis* (11). This reflects an emphasis on understanding how the public learns about and views nanotechnology, and is likely reflective of a large amount of funding given for these types of research, possibly stemming from an attempt to prevent or avoid some of the public relations issues experienced by other emerging technologies, such as GMO’s.14

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**Figure 3.1: Number of Social Science and Humanities Articles Containing “nano…” by Year**

![Number of Articles by Year](image_url)
Looking at the article codes themselves, we can also see a large emphasis on articles studying issues surrounding public perception and values. Institutional Governance and Deliberation and Engagement were also topics addressed in many papers within the sample.

The code “Addresses nanomanufacturing lab practices or applications” was not one of the original codes from Shapira et al., and ended up being applied to a significant number of articles, as many mentioned nanotechnology applications in some way, and we applied this code fairly liberally. Only a few articles under this code addressed nanomanufacturing lab practices. While the meaning of this code may be somewhat
ambiguous, it is notable that many articles do address specific applications, since a criticism that could be leveled at early nano-social-science literature was that it was too focused on nanotechnology as an abstract concept, instead of as a concrete technology with specific applications.

![Code Distribution](image)

**Figure 3.3: Number of Social Science and Humanities Articles Containing “nano…” by Code (note that some articles were coded under multiple codes, and thus the numbers in this figure do not add to 100).**

More insight may be gained by looking at the distribution of articles coded under the different categories over time (see Figure 3.4). Observations should be prefaced by saying that because we selected articles by citation rank, it is natural that this will tend to bias the search toward older articles, as it takes time for most articles to accumulate citations. Also, it should be noted that some articles were coded under multiple categories, so the sum of the number of articles coded under all categories in a given year may be greater than the number of articles in that year (as shown in Figure 3.1).
Figure 3.4: Number of Code Occurrences by Year – Code counts are presented based on the publication years of the articles coded. This graphic provides insight into what themes were more prevalent in certain years, illustrating the changing priorities of social scientists studying nanotechnology over time.

Articles primarily regarding predictions and visions of the future of nanotechnology peaked around 2005, two years after the passage of the 21st Century Nanotechnology Research and Development Act. At this point, it is likely that social
scientists were transitioning from visioning about potential futures to dealing with the reality of the nanotechnologies that were beginning to be developed.

According to this data, articles mentioning ethics were also more prevalent at the beginning of the sample, peaking around 2005. However, this shows one of the limitations of this data collection methodology, because there is a whole journal devoted to nanotechnology ethics, NanoEthics, and it is likely that through the methodology that was used in this study, not all of these articles were captured.

Articles addressing institutional governance, public perception and values, deliberation and engagement, and nanomanufacturing lab practices and applications peaked around 2008-2009. Articles whose audience or subjects explicitly included lab workers or scientists, as well as toxicology and risk assessment articles peaked slightly later, around 2010.

**Literature Search Conclusions**

While the methodology used in this work undoubtedly influenced (and may have restricted) the types of articles that were found and analyzed, this study gives valuable insights into the sorts of articles that a nanomanufacturing practitioner might come across while looking for articles using the search constraints that were used here. From other explorations of the overall body of social science literature on nanotechnology, there are areas of research that are underrepresented in this sample, such as bibliometric article analysis.

However, the overall lesson of this study is less about the areas of study found, and more about the audiences of the articles examined here. Out of the 100 articles examined, less than one fifth addressed the practitioners in the field under study directly.
Social science scholarship on nanotechnology was funded to provide societal context for this field, but as can be seen here, that context is often not directed at the researchers advancing nanotechnology, even though they may be the ones for whom this information is the most important.
CHAPTER FOUR: INTERVIEW OBJECTIVES AND METHODOLOGY

The objective of these interviews, which were part of the larger case study of the SNM project as a collaboration between Boise State University and Micron Technology, was to collect information from talking with those involved with the SNM project to gain insights into the overall function of the project and the academic-industry relationship therein, as well as how this might impact the commercialization of the technologies under development. Since we were interested in collecting experiences and thoughts about the project, and less interested in statistical analysis of the results, semi-structured interviews with an interview guide were a natural choice.

The use of an interview guide, according to Tracy, “is meant to stimulate discussion rather than dictate it.” By allowing the conversation to go in unexpected directions, we allowed for the possibility that the people we were interviewing might have useful information that we had not thought to ask them about. It is also possible that, through the discourse of conversation between the interviewer(s) and the interviewee, that the interviewee might come to additional insights that they had not previously thought of.

This method also allows the interviewer more flexibility to re-phrase questions to make them clearer to the interviewee, or to skip questions if they have already been addressed in the discussion of previous questions, or if they are not relevant to the particular interviewee. This was important, considering the variation within the sample.
of respondents’ levels of direct engagement with the SNM project, as well as their
different jobs and organizations.

Data Collection

As our list of interviewees included both researchers and administrators, we had
two versions of the interview guide – one for each group. Three questions were omitted
from the interview guide for administrators (these were more project-specific questions,
and most of the administrators that we interviewed were not directly involved with the
SNM project). Some of the question phrasing was also changed to make it more
appropriate for each group. The two interview guides can be seen in Appendix C. The
questions included in the two versions of the interview guides were guides for what to
ask, but the actual wording of the question asked varied somewhat between interviews.

Interviews were conducted alongside Dr. Eric Lindquist. Most of the interviews
were conducted with two interviewers present, which was the ideal case, as one could
focus on asking questions and maintaining the flow of the conversation, while the other
took notes. However, several interviews were conducted with only one interviewer, due
to scheduling conflicts.

Interviewers took hand-written notes and typed them up after the interviews,
which were not recorded. There was concern that, since there were some sensitive
political and intellectual property aspects of the project situation, interviewees might have
been less forthcoming if every word that they said was being recorded. Depoy and Gitlin
cite this notion in their book, stating “There are several considerations in using voice
recording. First, decide whether recording will be intrusive in your setting and will
prevent informants from expressing private thoughts.” Not recording the interviews
also lessened the amount of time necessary to spend “processing” the data after the interview, as there was no need for verbatim transcription of recordings. The interviews were conducted under IRB #041-SB16-106 (OSP proposal #:5923). IRB documents may be found in Appendix B.

**Research Questions**

The intent of these interviews was to probe the experiences of researchers and research administrators associated with the SNM project and similar projects at partner institutions, in regards to university-industry partnerships, as well as the interviewees' perception of how their work impacts the public and how the public might perceive their work. The latter perceptions are of interest, as past experience from other industries (such as GMO’s) indicates that considering public opinion and how new research is communicated to the public can impact the successful commercialization of a technology produced from this research. To this end, the interview questions aimed to increase our understanding of the answers to the following questions:

1. What are the opportunities and challenges of academic-industry partnerships like this joint project?
2. What does the academic-industry relationship in this case study (the project with Boise State University and Micron Technology) look like? Is this consistent with interviewees' past experiences with such projects (if any)?
3. What do interviewees believe are the societal implications of the rise of nanomanufacturing? Is this something that they think about very often?
4. Have interviewees' past experiences in academic-industry partnerships (or their experiences on the current project) shaped their willingness to participate in university-industry partnerships?
5. What do researchers and administrators feel are the most significant factors in university-industry partnerships that can prevent the commercialization of new technologies (especially nanotechnologies)?

6. How much interaction and active collaboration has there been between the different parties in this project?

**Crafting the Interview Guide**

The balance required when conducting qualitative interviews with an interview guide is to craft questions that are sufficiently open-ended to accommodate discussion of unexpected subjects, while still ensuring that the conversation is directed toward answering the research questions of the project. To this end, it is helpful to consider the assumptions that we had about the respondents’ answers, though we worked to craft questions in a way that did not influence answers based on these assumptions.

It was expected that some of the researchers might have considered the social or ethical dimensions of the technologies that they developed, but that many of them would not consider this something that they thought of on a day-to-day basis, if at all. To this end, the “elevator question” (Question 8 on both interview guides – see Appendix C) was a less overt way to assess these thoughts than asking outright (though this subject was also addressed more overtly in Question 4 on both interview guides – see Appendix C).

It was also anticipated that many of the administrators that were interviewed would have little, if any, direct knowledge of or involvement with the SNM project, but that many of them would have had some past or present experience with academic-industry partnerships (especially since this was one of the main reasons for selection of the interviewees).

Given the variation in career stages of the interviewees, it seemed likely that there would be a variation in the level of prior involvement in academic-industry partnerships,
though we were unsure how this would affect the level of interest that interviewees had in
engaging in such partnerships in the future.

With these assumptions in mind, we set about crafting interview questions that we
believed would lead to answering our research questions, while not biasing the
interviewee’s answers. Tracy outlines some best practices for wording interview
questions, which we observed, including\textsuperscript{70}:

- Questions should be simple, clear, and free of jargon (this was especially
  important since we were trying to use most questions for both groups –
  researchers and administrators).
- Ask only one thing with each question (no “double barreled questions”).
- Follow yes/no questions with follow-ups, such as “Why?” to encourage more
  complex answers.
- Word questions in such a way that they do not lead the respondent to answer one
  way or the other (no “leading questions”).
- In general, questions should be accompanied with probes, such as asking for an
  example or an anecdote.

Following such guidelines helped to ensure that the questions asked in the interview
guides would not bias the answers of the interviewees.

Several questions in the interview guides are “matched pairs”, where one asks for
positive responses about a subject, then the next asks for negative responses about the
same subject, such as “opportunities” and “challenges”. This was also done in an attempt
to not bias interviewees towards positive or negative responses about a subject by giving
each equal weight. In interviews, these questions were sometimes posed at the same
time, so that interviewees could think about their answers to both simultaneously, as positive and negative answers on a common subject were often intermingled in conversation.

**Interviewee Selection**

To date, all interviewees have been either from Boise State or Micron, and the research presented here focuses on the relationship between Boise State and Micron. Interviewees were selected from the following categories:

- Faculty and Micron researchers involved directly with the SNM project as Principle Investigators (PI’s).
- Non-PI faculty involved with the project (current and past).
- Lead Ph.D. students involved with each section of the project.
- Research administrators involved in setting up the SNM grant.
- Research administrators involved in other similar academic-industry projects around campus, including faculty and staff from the College of Engineering and the Division of Research and Economic Development.
- Names suggested by other interviewees (snowball sampling).

Interviews were conducted with a group of 13 people, consisting of researchers and administrators from Boise State University, as well as from Micron Technology. The names of those interviewed are not included here, as interviewees were promised confidentiality as part of the Informed Consent process. While it is difficult to maintain anonymity within a sample size of 13 interviewees (a fact which was acknowledged in the Informed Consent form that each interviewee signed before their interview), identities
are shielded here by not mentioning interviewees’ job titles, as well as by aggregating
responses into general conclusions.

Future work in the final year of the SNM project should include a broader range
of interviews, including with researchers and administrators at Harvard, and industry
liaisons at other semiconductor manufacturing companies that participate in the
Semiconductor Research Corporation (SRC).

Data Processing and Analysis

Hand-written field notes from the interviews were transferred into Microsoft
Word documents, with interviewers filling in context and details as appropriate (denoted
as separate from the main text of the interviewee’s responses). These notes were then
transferred into Nvivo, a qualitative data analysis software. Nvivo allows researchers to
organize quotes from interview data into themes (called “nodes” in Nvivo). This
organization process, referred to as “coding”, is helpful to identify trends in what was
said across multiple interviews. These trends were then used to aggregate specific ideas
from each interview into broader observations. This aggregation was important to draw
broader conclusions, but was also necessary to help protect the anonymity of the
interviewees.

Nodes used for coding were generated in two ways. Initial nodes were generated
based on the research questions listed above, as well as other themes anticipated to
appear in one or more interviews. As interviews were coded, if themes of interest that
did not fall into an existing node were discovered, new nodes were created. Some nodes
were organized into hierarchies, based on related themes. A full listing of all node names
and hierarchies may be found in Appendix D.
CHAPTER FIVE: RESULTS AND DISCUSSION

As was mentioned above in the Methods section, this thesis focuses on the relationship between Boise State and Micron. To protect the anonymity of the interviewees, ideas and themes discussed have been aggregated up to a broad-level discussion, without mention of the name or position of those who put forth the ideas. Some additional observations are included from my personal involvement with the project – specifically, shadowing the student research team working on the deposition side of the project for several months.

The interview questions included in the interview guides (see Appendix C for details) were intended to probe several broad subjects, based on the research questions outlined in Chapter Four. Responses to each subject are presented below.

**Opportunities of Academic-Industry Partnerships**

Academic-Industry partnerships can offer many advantages for all concerned, and can be fertile ground for new ideas. Universities can benefit by receiving materials or resources from companies, strengthening relationships with industry, and through opportunities for their students. Companies in industry can have access to exploratory research and development that they might have trouble justifying performing themselves. The following section outlines these advantages in more detail for each of the parties involved.
For University Researchers

In response to questions regarding the benefits of academic-industry partnerships, interviewees cited the following benefits for university researchers. University researchers generally benefit from partnerships with industry through access to more resources (either financial or materials), as well as often through access to industry expertise in the area of their project. This could be through characterization or access to a process that the university researchers do not have the capabilities to do, or it could come in the form of interactions with industry scientists and engineers. In the case of the SNM project, researchers at Boise State University received over 20 types of wafers with different surfaces on which to experiment with DNA deposition, as well as access to a research scientist at Micron who could provide insights into what is realistic and necessary to scale a product or process into manufacturing in Micron’s facilities. For a project focused on scaling products into manufacturing, these insights are very valuable.

Beyond the exchange of materials, projects such as the SNM, when successful, can form the basis for other collaborations between the parties involved. In the case of the SNM project, at the time of this writing, the Nanoscale Materials and Device Group (NMDG) currently has another project in collaboration with Micron, focused on Nucleic Acid Memory (NAM), which is funded by the Micron Foundation, as well as the Semiconductor Research Corporation (SRC), Functional Accelerated nanoMaterial Engineering (FAME) Center.

For Universities

When discussing benefits of academic-industry partnerships for universities, interviewees gave the following answers. Relationships built through academic-industry
partnerships bring benefits beyond those specific to the researchers involved. Successful partnerships with industry can build or reinforce institution-level relationships between companies in industry and universities. Boise State and Micron have had a long-standing relationship that has included many gifts from Micron to Boise State, including a recent $25 million gift from the Micron Foundation to build a new Center for Materials Research. As part of this gift, the Materials Science and Engineering Department at Boise State is now the Micron School of Materials Science and Engineering. The success of projects such as the SNM can cement these ties and allow companies a way to see a return on their investment into the university.

Through working closely with industry, universities and university administrators can also gain deeper insights into the skills that companies need and expect students to gain through their university education. This can make students more competitive when seeking industry jobs, and universities more competitive if they can demonstrate high levels of student placement into industry. Having faculty doing cutting-edge, industry-relevant research can also give universities a competitive edge in marketing themselves, especially as graduate institutions.

One of the mandates of a state university is to disseminate its research through technology transfer. Partnerships with industry can be one way to do this, through mechanisms such as IP agreements or licensing.

For Students

In response to questions regarding the benefits of academic-industry partnerships, interviewees cited the following benefits for students. Students can benefit greatly from academic-industry partnerships in a number of ways. Student researchers working on the
project can gain technical experience, and graduate students can find thesis or dissertation topics. Whether directly through the project, or through connections made by faculty to industry, academic-industry partnerships can open pathways for students to get jobs or internships at partner companies.

On the SNM project, these benefits are evident, as four students from the NMDG (graduate and undergraduate) have been employed or become interns at Micron’s Boise site after working on the SNM project, or on a related senior project team through the Micron School of Materials Science (this team focused on electrophoretic deposition of DNA, a related and parallel goal to that of the SNM project). The two lead Ph.D. students (one for the deposition side of the project and one for the metrology side) have also gained research topics and valuable research skills, and in one case, job opportunities, from working on the SNM project.

For Industry

Interviewees noted the following benefits for industry from partnerships with academia. Companies can benefit from partnerships with universities by gaining access to exploratory research and insights into new emerging technologies. While in the past, industry did basic science research and large-scale research and development at places like Bell Labs, without the technological monopolies of the past, many of these laboratories no longer exist, and such research is less common today. Through working with university researchers, companies can explore what works and what does not in these emerging technologies without having to devote their own in-house resources and people to the task. Industry researchers can also have direct access to university professors through these sorts of partnerships to exchange and vet ideas.
For companies, partnerships with universities can also be a way to reach out to potential future employees – university students. Through working directly with student researchers, or through presentations to university students as part of site visits, partnerships can give companies a chance to get students interested in working for industry and try to attract them to work for them.

**Challenges of Academic-Industry Partnerships**

While there are many potential benefits of academic-industry partnerships for all parties, interviewees cited several challenges and potential disadvantages to these sorts of partnerships, as well. Some of these disadvantages are relevant in projects that are unsuccessful, but some challenges are inherent to even the most successful academic-industry partnerships. Fundamentally, universities and companies in industry have different priorities, needs, and stakeholders. Companies must maintain their profit margins, often answering to shareholders who are concerned with short-term profits. On the other hand, universities have a mission to educate and (at least in the case of state universities) answer to the public and to their students as stakeholders. Universities focus on disseminating knowledge, while new ideas in industry are frequently kept as trade secrets. Institutions planning to embark on a university-industry partnership must identify, communicate about, and address such issues in order to ensure a successful partnership. The following section outlines these challenges and disadvantages in more detail for each of the parties involved.

**For University Researchers**

According to interviewees, for university researchers, one of the major potential disadvantages of a collaboration with industry is that they may lose some of their
intellectual freedom. Especially when funding for a project comes directly from industry (instead of from a federal agency, such as the NSF), there can be pressure to maintain focus on a pre-defined goal that may not allow room for researchers to pursue tangential avenues of inquiry which might otherwise become fruitful research subjects or contribute to the diversity of their research portfolio (it is generally desirable for faculty to pursue both applied and basic research topics). For both sides, the communication and collaboration required for a healthy academic-industry partnership can be time-consuming.

For Universities

For universities, interviewees noted that the most significant concerns in an academic-industry partnership are IP and maintaining relationships with industry partners. If a project involving an academic-industry partnership goes badly, it could potentially jeopardize the institution’s relationship with that company and threaten the possibility of future partnerships with them. Intellectual property agreements must also be properly negotiated to maintain the university’s control over its previous IP, while enabling and ensuring sharing of information relevant to the project between partners. If such arrangements are not negotiated prior to the start of the project, this could negatively impact the project timeline and progress. In the case of the relationship between Boise State and Micron, there are multiple department- and college-wide agreements in place with Micron that facilitate these sorts of exchanges.

For Industry

Interviewees suggested that companies may be hesitant to enter into an academic-industry partnership, and with good reason. While there are many benefits to these sorts
of partnerships, as mentioned above, many companies have been sued by universities over IP disagreements or infringement. This can happen through a company’s use of a university’s IP without proper licensing, but can also stem from industry researchers becoming intellectually “contaminated” after seeing or hearing of an idea in a university lab and later, possibly unknowingly, using aspects of this idea in another project at the company where they work. These sorts of IP disputes mean that agreements must be worked out for IP sharing before a project can go forward, adding time and bureaucratic steps to the process of setting up a partnership.

For engineers or scientists in industry, embarking on such a partnership can be a taxing prospect, as their responsibilities as a liaison with the university may be in addition to their normal workload at the company. This can lead to tensions with university partners (who are also often overcommitted), as industry researchers may be difficult to reach or schedule meetings with because of their work schedule. It is also possible that the company may not yet have the culture or structures in place to support academic-industry partnerships and those engaging in them. Liaisons may be under pressure to make sure that the project produces results that can be shown to their management, demonstrating that the project advances the company’s interests or bottom line, or at least is creating impact through publications.

While industry researchers may be busy and difficult to reach, university faculty and students also have many demands on their time (the only possible exception to this is postdoctoral researchers), meaning that university research projects often move at a fraction of the speed of an equivalent project in industry. Many university research groups also have more limited resources than their counterparts in industry, which can
also impact the speed of the project, especially since it may limit the number of people working on the project. Furthermore, since the mission of academic research labs is, at its core, to educate through research, the untrained nature of their workforce is fundamental to their operation. PI’s, especially, often have many demands on their time (teaching, research, grant-writing, managing students, serving on committees, etc.), and may only have a small portion of their salary coming from any one grant, which can sometimes equate to an equivalently small amount of their time devoted to the project.

**Societal Implications**

One area of interest from the project’s research questions was how frequently and to what degree researchers and administrators on the project considered the societal and ethical implications of their work and of the project. This was measured in part via a question, which asked interviewees to come up with a fictional pitch to the Idaho Governor regarding the impact of their research on the people of the state of Idaho.

While all those interviewed had some thoughts on the subject of societal and ethical implications, some interviewees (mainly researchers) were not immediately conscious of having considered these implications, or said that they only think of them occasionally. Another frequent comment from those directly associated with the SNM project was that the project was not directly involved with producing a product, and thus that the potential implications of the project and the materials and techniques it is working to develop were not of immediate importance.

Many interviewees mentioned local industry as part of their “elevator pitch”, noting that technological advancements that benefit Micron would also benefit the local
Also frequently mentioned was the importance of an educated workforce, and how this is also beneficial to the local community and industry.

**Relationship Between Partners**

**Boise State University and Micron Technology**

As one of the major technology companies and employers in the Treasure Valley (in Southwestern Idaho) and longtime support of Boise State, Micron already has a fairly close relationship with Boise State on an institutional level. On a project level, Micron has been fairly engaged, with regular meetings between Micron and Boise State researchers occurring the first two years of the SNM grant. A member of the management chain at Micron responsible for overseeing the SNM and other similar projects is also part of the Industrial Advisory Board of the Micron School of Materials at Boise State.

**Within Boise State**

Regular research update meetings were held with researchers from Boise State involved in different aspects of the SNM and related projects, ensuring that the Boise State teams were aware of each other’s progress and were able to provide feedback to each other.

**Past Experiences**

Many of the interviewees mentioned that they had some prior experience with academic-industry partnerships, though in some cases, they were indirect relationships, or collaborations that involved only the exchange of materials with little communication. One researcher mentioned that their experience working with a company in industry had increased their interest in pursuing industry-related research. Another researcher noted
that their interest in pursuing partnerships with industry was motivated by creating connections to benefit students. Most of the administrators interviewed had extensive experience dealing with academic-industry partnerships.

**Impact on Willingness to Engage in Academic-Industry Partnerships**

With mixed levels of past industry engagement across the pool of interviewees, all expressed some level of willingness to participate in another academic-industry partnership in the future, though some qualified with caveats about partner alignment or relevance to their work. While a sample size of 13 is far too small to draw any quantitative conclusions, in this case it seems that while some interviewees’ past experiences informed their consideration of whether or not to pursue academic-industry partnerships, their current level of engagement with such projects was probably a stronger factor in this matter.

**Barriers to Commercialization**

Several common themes emerged from the interviews, related to challenges in academic-industry partnerships that could become barriers to commercialization. Many interviewees alluded to challenges surrounding intellectual property – agreements to share it, concerns over lawsuits, getting necessary information from collaborators, and disseminating research knowledge were among the top concerns.

Another significant challenge is that of maintaining the relationships between people and institutions required for such a partnership. Organization-wide policies and culture can create barriers, even if individual researchers and administrators are in agreement. The inherently mismatched needs and timelines of industry and academia are a common barrier which must be addressed and re-addressed throughout the partnership
to make sure that all partners feel that their needs are being met. Competing demands on the time of all parties involved – both in industry and in academia – can make these frequent communications challenging, but their importance must not be underestimated. This is especially true of PI’s, whose responsibility it is to maintain inter-institutional relationships and make sure that the project is on track.

Lastly, a set of challenges that must not be overlooked in the planning and execution of academic-industry partnerships focused on developing new technologies are the technical challenges of accomplishing the project goals. While transformative change rarely happens without big ideas, it is important for project timelines and deliverables to be as realistic as possible from the beginning.

Other Subjects Discussed

Nanotechnology, Research, and the Public

Public Awareness, Understanding, and Acceptance

Most interviewees agreed that the public, in general, does not know enough about the technology involved in the SNM project (or many other technologies under development at their institutions) to understand such technologies and know whether or not they accept them. If a technology was integrated into Micron’s manufacturing process, as long as it was not part of the finished product, many interviewees felt that there was a significant chance that no one in the public would be aware.

One interviewee cited a general lack of technical knowledge among the public, making discussions of the merits and drawbacks of potential technologies difficult. Required engineering courses for all students were suggested as a solution to this.
Communicating with the Public

Framing has a significant influence on the general public’s perception of a new technology. This includes not only how researchers communicate their research to the public, but also what gets attention in the media.

Senior Projects

Senior projects are one way that students can get early exposure to working with industry. Maintaining engagement from industry partners is especially critical in these projects, as students need guidance and communication with sponsors to learn and do well with their projects. There was a senior project related to the SNM project, focused on electrophoretic deposition of DNA, which provided experience and education value to four students, two of whom are employed at Micron at the time of this writing. Senior projects such as this one can provide a platform for research groups to pilot intellectually risky concepts in a context where learning will be derived, regardless of the outcome of the project. If such a project is successful, this could lead to future grant opportunities.

Some of the lessons taken from maintaining good senior project relationships with industry also apply to research relationships with industry. Maintaining communication, trust, and engagement is key for establishing good long-term relationships with industry sponsors that can lead to multiple senior projects, over time. These strategies apply equally well to more traditional research partnerships, as well.

Lessons Learned

Interviewees were asked to articulate lessons that they had learned through their involvement in the SNM project, or with regards to academic-industry partnerships in
general, based on their experiences. These lessons can largely be distilled into a few key categories, with significant amounts of overlap between interviews on some points.

Communication, Relationships, and Time Commitment

Possibly the most resounding and frequently repeated recommendation was the importance of communication and maintaining an open, trusting relationship between partners on a project. At least a quarter of all of the comments about lessons had something to do with communication or rapport. While this may be unsurprising, communication and relationship maintenance between partners, especially if they are off-campus or in another state or country, can be difficult to maintain. The following is a summary of suggestions that interviewees put forth on this topic:

- Communication must be frequent and open, with all parties feeling comfortable sharing their needs and challenges.
- All parties involved in such partnerships likely have other demands on their time. This must be taken into consideration when collaborators are slow to respond. However, all parties must also devote adequate time to allow frequent communication to happen. It is important that each side feels like their time investment in the project is being respected.
- A plan should be established at the beginning of the project, not just for what research will be done, but what each collaborator will get out of the project. Being clear about expectations such as authorship and publications upfront can avoid conflict later on. This plan should be referred to regularly, to make sure that the project is going in the right direction and is on track.
• All sides should do their best to be realistic with what they can accomplish, and on what timeline, then make every effort to stay on this schedule. However, if a milestone falls behind, or something is not able to be accomplished, it is important to be open and honest with collaborators about these situations.

• A lesson from senior projects: Establishing relationships, trust, and maintaining connections are important to forming a long-term rapport with a company that can lead to multiple partnerships.

**Aligning Needs and Priorities, Recognizing Differences**

By nature, industry and academia have fundamental differences that impact how researchers and administrators in each sphere do their jobs. Acknowledging these differences and keeping them in mind can help significantly in maintaining relationships between partners on both sides. The following is a summary of suggestions that interviewees put forth on this topic:

• Be aware of the different missions and needs of each side. In academia, reward structures are built around the dissemination of knowledge, usually through publishing. However, it may be in the best interest of a company to keep some ideas secret to protect their IP. These differences must be discussed, and a compromise reached which serves both sides’ needs as much as possible.

• Timelines are different between academia and industry. In industry, projects often move very quickly, and missing deadlines can have serious financial and other consequences. Academic partners must be sensitive to this. At the same time, faculty and students in academia have many demands on their time, and often have more limited resources than industry, so projects tend to move more
slowly, by nature. Both sides must be aware of these differences and meet in the middle with concrete timelines and goals.

- Even the general style of communication is different between academia and industry. While presentations in academia often focus on what has been accomplished on a project, presentations in industry may focus more on what is going wrong and what needs to be fixed, in order to focus efforts on solving the intermediate problems needed to accomplish the overall goal.

Other Lessons

A number of other ideas, solutions, and lessons were also put forth that do not fit as neatly into categories as those above. However, they may be helpful to keep in mind for future partnerships.

- When choosing where to invest resources, focus more on people who are neutral or somewhat engaged with an idea (such as the merits of partnering with industry). Those who are disengaged may not respond as strongly to time and resources, and may be less likely to produce the desired results.

- One interviewee observed a seeming lack of methods for researchers to analyze the potential risks of the technologies they are developing, and suggested that the Failure Mode Effects Analysis (FMEA) process could be applied to thinking about these risks, in the same way that it is used in industry to consider the possible repercussions of changing a manufacturing process in industry.

- While programs exist such as the NSF Industry/University Cooperative Research Centers (I/U-CRC), which mandate collaboration with industry, the Scalable Nanomanufacturing Program has no such requirement. However, one interviewee
noted that having the insights of an industry partner who has experience in manufacturing and scaling technologies into manufacturing is invaluable to avoid “re-inventing the wheel”, when it comes to technology scaling.
CHAPTER SIX: CONCLUSION

Nanotechnology is an emerging technology field that has yielded many discoveries in the past two decades, and has already begun to be integrated into consumer products. However, many advances in nanotechnology research have not yet been commercialized. One step in the process of commercializing a technology produced in an academic lab is technology transfer. Partnerships between academia and industry are one way that technological ideas can be transferred into industry, with the possibility of becoming integrated into products. One industry where advances in nanotechnology research could be of great impact is in the semiconductor industry, where the drive to shrink feature sizes demand that industry look for new alternatives to traditional technologies, which are reaching their limits.

In the case study presented here, researchers and administrators, mostly related to a nanotechnology research project aimed at addressing some of the manufacturing challenges faced by the semiconductor industry, the SNM project, were interviewed about their experiences on the project and with academic-industry partnerships in general. From these interviews, observations were made about the challenges and opportunities of academic-industry partnerships, and lessons and suggestions were captured that can be applied to improving future partnerships.

Interviewees overwhelmingly identified communication and relationship-building between project partners as an area that is important to focus on in academic-industry partnerships. Academia and industry have very different cultures, communication styles,
needs, stakeholders, and timelines, and these differences must be openly addressed and considered throughout the process to ensure the success of a partnership project. Intellectual property was also identified as a key sticking point that should be addressed at the beginning of any partnership, particularly between academia and industry. Realistic timelines and project milestones were suggested as important for keeping projects on track and providing timely results to reinforce the value of projects to industry management.

While the technical challenges of nanotechnology are significant, it is important that researchers consider factors outside the lab that may also impact the success and significance of their projects. Whether part of a partnership or not, it is important for all researchers to be aware of the politics, regulations, and public perception (or awareness) of the work that they do. For those involved in partnerships with industry, managing the dynamics of the relationship between project partners might seem secondary to research goals, but can be as critical to the success of the project as any fundamental technical detail or equipment.
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APPENDIX A

List of Literature Survey Articles
### Articles from Literature Survey Sample Set

The following list includes the citation information for the top 100 articles that were coded in the project described in Ch. 3 – Literature Survey. The number assigned to each article indicates its citation rank, according to Web of Science, with 1 indicating the most cited article in the sample and 100 indicating the least cited.

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<td>90</td>
<td>Donk, Andre, Julia Metag, Matthias Kohring, and Frank Marcinkowski. “Framing Emerging Technologies: Risk Perceptions of Nanotechnology in the German Press.” <em>SCIENCE COMMUNICATION</em></td>
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APPENDIX B

Institutional Review Board Documents for Interviews
Date: May 26, 2016
To: Eric Lindquist
From: Social & Behavioral Institutional Review Board (SB-IRB)
c/o Office of Research Compliance (ORC)
Subject: SB-IRB Notification of Approval - Original - 041-SB16-106
Nanomanufacturing Outside the Lab: A Case Study in Academic-Industry Partnerships

The Boise State University IRB has approved your protocol submission. Your protocol is in compliance with this institution’s Federal Wide Assurance (#0000097) and the DHHS Regulations for the Protection of Human Subjects (45 CFR 46).

Protocol Number: 041-SB16-106
Expired: 5/25/2017
Received: 5/19/2016
Review: Expedited
Approved: 5/26/2016
Category: 7

Your approved protocol is effective until 5/25/2017. To remain open, your protocol must be renewed on an annual basis and cannot be renewed beyond 5/25/2019. For the activities to continue beyond 5/25/2019, a new protocol application must be submitted.

ORC will notify you of the protocol’s upcoming expiration roughly 30 days prior to 5/25/2017. You, as the PI, have the primary responsibility to ensure any forms are submitted in a timely manner for the approved activities to continue. If the protocol is not renewed before 5/25/2017, the protocol will be closed. If you wish to continue the activities after the protocol is closed, you must submit a new protocol application for SB-IRB review and approval.

You must notify the SB-IRB of any additions or changes to your approved protocol using a Modification Form. The SB-IRB must review and approve the modifications before they can begin. When your activities are complete or discontinued, please submit a Final Report. An executive summary or other documents with the results of the research may be included.

All forms are available on the ORC website at [http://kooc.al/D2PYTV](http://kooc.al/D2PYTV)

Please direct any questions or concerns to ORC at 426-5401 or humansubjects@boisestate.edu.

Thank you and good luck with your research.

Dr. Mary Pritchard
Chair
Boise State University Social & Behavioral Insitutional Review Board
APPENDIX C

Interview Guides
Reproduced below are the two interview guides used to conduct the case study interviews for the results which are presented in this thesis. There are two versions of the guide: one for the researchers involved with the SNM project, and one for interviewees in more administrative capacities. Each included the research questions printed on the first page as they are here, as a reminder to the interviewer of what broader questions they looking for answers to during the interview.

All questions are the same between guides, with the exception of the “broad” and “narrow” sections, which were modified to fit more appropriately for each group. Question 7 was omitted in almost all interviews (mostly the later ones), as it was found to be largely redundant with other questions in the guide. However, it was still printed in the guide (though in later interviews, it was printed with a strikethrough) to maintain the numbering of the other questions.
Nanomanufacturing Case Study Interview Guide

Broad Overall Research Questions (for interviewer to keep in mind)
- What can we learn to increase our understanding of societal implications related to the rise of nanomanufacturing?
- What does the academic-industry relationship in this case study look like?

Specific Research Questions
I. What do interviewees believe are the societal implications of the rise of nanomanufacturing? Is this something that they think about very often?
II. What does the academic-industry relationship in this case study (the project with Boise State, Micron, and Harvard) look like? Is this consistent with interviewees' past experiences with such projects (if any)?
III. What are the opportunities and challenges of academic-industry partnerships like this joint project?
IV. Have interviewees' past experiences in academic-industry partnerships (or their experiences on the current project) shaped their willingness to participate in university-industry partnerships?
V. What do researchers and administrators feel are the most significant factors in university-industry partnerships that can prevent the commercialization of new technologies (especially nanotechnologies)?
VI. How much interaction and active collaboration has there been between the different parties in this project?

Introduction: All Respondents
1. What is your current position?

2. What is your role on the SNM Project (as defined in the proposal)?
Note: There are two, slightly different, versions of the “Broad” and “Narrow” sections – one for researchers and one for research administrators

Broad: Researchers

3. Have you been involved in an academic-industry partnership in the past? Can you describe the project and your role?

4. In regards to integrating nanotechnology into industrial applications, are you concerned with societal and ethical implications? If yes, why? If no, why not?

5. Do you think that the public generally accepts/understands what you’re trying to do?

6. What challenges (related to public acceptance) for the industry do you see coming up in the future?
7. How often do you think of the societal implications of your work? Can you give an example? Have you ever had to justify what you do from a societal implications perspective?

8. If you were in an elevator with Governor Otter, what would you tell him to justify how your work is useful to the people of the state of Idaho? [For those outside of Idaho, broaden to “If you were in an elevator with the governor of your state, what would you tell them to justify how your work is useful to the people of your state?”]

Narrow: Researchers

9. What challenges have you encountered in the project so far?
10. What opportunities have you found from the project so far?

11. How successful do you feel you’ve been in accomplishing your part of the project so far? Are you on track with your proposed schedule? Why or why not?

12. How would you describe your level of interaction with people involved in other parts of the SNM Project?

Reflect: All Respondents

13. What do you think can be learned from the SNM project that could be applied to future partnerships between universities and industry?
14. What do you feel are the advantages of partnerships between universities and industry (in general)? Do you see those in the SNM project?

15. What do you feel are the disadvantages of partnerships between universities and industry (in general)? Do you see those in the SNM project?

16. Do you think you will enter into another university-industry partnership in the future, if given the chance? Will you seek one out? [For administrators: Do you think that you will work on setting up another university-industry partnership in the future? Will you actively seek out such partnerships for your university?]

17. Do you have any general thoughts on what you have learned from your experience on the SNM project?
Nanomanufacturing Case Study Interview Guide

Broad Overall Research Questions (for interviewer to keep in mind)

- What can we learn to increase our understanding of societal implications related to the rise of nanomanufacturing?
- What does the academic-industry relationship in this case study look like?

Specific Research Questions

I. What do interviewees believe are the societal implications of the rise of nanomanufacturing? Is this something that they think about very often?

II. What does the academic-industry relationship in this case study (the project with Boise State, Micron, and Harvard) look like? Is this consistent with interviewees’ past experiences with such projects (if any)?

III. What are the opportunities and challenges of academic-industry partnerships like this joint project?

IV. Have interviewees’ past experiences in academic-industry partnerships (or their experiences on the current project) shaped their willingness to participate in university-industry partnerships?

V. What do researchers and administrators feel are the most significant factors in university-industry partnerships that can prevent the commercialization of new technologies (especially nanotechnologies)?

VI. How much interaction and active collaboration has there been between the different parties in this project?

Introduction: All Respondents

1. What is your current position (and can you share a bit about your background and how you got there)?

2. What is your role on the SNM Project (as defined in the proposal)?
Note: There are two, slightly different, versions of the “Broad” and “Narrow” sections – one for researchers and one for research administrators

Broad: Administrators

3. Have you been involved in an academic-industry research partnership in the past? Can you briefly describe the project and your role?

4. In regards to integrating nanotechnology into industrial applications, are you concerned with societal and ethical implications? If yes, why? If no, why not?
5. Do you think that the public generally accepts/understands what you're trying to do?

6. What challenges (related to public acceptance) for the industry do you see coming up in the future?

7. How often do you think of the societal implications of your work? Can you give an example? Have you ever had to justify what you do from a societal implications perspective?
8. If you were in an elevator with Governor Otter, what would you tell him to justify how your work is useful to the people of the state of Idaho? (Possibly broaden to “If you were in an elevator with the governor of your state, what would you tell them to justify how your work is useful to the people of your state?”, since not all interviewees will be in Idaho)

Reflect: All Respondents

9. What do you think can be learned from the SNM project that could be applied to future partnerships between universities and industry?

10. What do you feel are the advantages of partnerships between universities and industry (in general)? Do you see those in the SNM project?
11. What do you feel are the disadvantages of partnerships between universities and industry (in general)? Do you see those in the SNM project?

16. Do you think you will enter into another university-industry partnership in the future, if given the chance? Will you seek one out? [For administrators: Do you think that you will work on setting up another university-industry partnership in the future? Will you actively seek out such partnerships for your university?]

17. Do you have any general thoughts on what you have learned from your experience on the SNM project?
APPENDIX D

Code Hierarchy Diagram