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NANOTECHNOLOGY WORKFORCE PIPELINE CHALLENGES

A Current Assessment and The Future Outlook

by

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Report to **The American Society Mechanical Engineers** to fulfill the research requirements of the Washington Internships for Students of Engineering for the summer 2001 program.

WISE
Washington Internships for Students of Engineering

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Abstract

Nanotechnology is a truly amazing field that enables novel applications and offers improvements on today's technologies. The unique technical nature of the field, the high level of government and private funding, and overall enthusiasm, combined with an intersecting market-pull and technology-push create the potential for rapid growth at the nanoscale, but also forces us to assess our ability to fill the workforce pipeline so we can capitalize on these advances. Currently, the need for nanotechnology workers is for MS/PhD level researchers and for technicians. However, people whose work and training lies in between the researchers and technicians will ultimately become the workforce of the nano generation. Two factors lead to concerns of a shortfall in the pipeline: struggles in America with science, technology, and engineering education, from the K12 level through graduate schools, and a lack of awareness of the nature of the nanoscale.

In addressing this situation, the value of partnerships, between federal government, universities, state government, local school districts, and/or industry cannot be understated. Pockets of successes near NNUN centers where state, federal, industry, and private dollars have intersected serve as powerful evidence of this. Partnerships between schools and universities can be used to attack the root of science and technology workforce pipeline challenges and reduce ignorance about nanotechnology. Government laboratories and agencies can work with universities to fund research that leverages the pool of graduate students. Perhaps the most valuable characteristics of partnerships is that they can lead to the synthesis of science and engineering, giving the skills required to succeed in this interdisciplinary field and building an overall strong scientific and technical base. The field is ripe with opportunity, but we also face challenges from overseas, so a sound nanotechnology policy is critical.

About the Author

Brian Pandya is a student in the Department of Mechanical and Nuclear Engineering at The Pennsylvania State University. This paper is the culmination of ten weeks of research as part of the Washington Internships for Students of Engineering.

At Penn State, Pandya is a member of the Schreyer Honors College and the recipient of six scholarships. During the 2001-2002 academic year, he is working with Professor Gary Settles on the Schlieren imaging of musical tones for his senior honors thesis in the Gas Dynamics Laboratory. In March 2001, Pandya was elected by his peers to serve as president of the Penn State ASME chapter. He can be reached via email at *bpandya@psu.edu*.

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Info on the WISE Program

Founded in 1980, the Washington Internships for Students of Engineering has become one of the premier Washington internship programs. Its goal is to groom future leaders of the engineering profession who are aware of and can contribute to the important intersections of technology and public policy.

Approximately 15 outstanding engineering students in the final year of undergraduate study are selected each year in a nation-wide competition to spend ten weeks in the summer in Washington, D.C. During the internship, they learn how government officials make decisions on complex technological issues and how engineers can contribute to legislative and regulatory public policy decisions. Throughout the ten weeks, the students interact with leaders in the Congress and the Administration, industry, and prominent non-governmental organizations. Meetings with congressional Committees, executive office departments, and corporate government affairs offices are daily activities.

In addition, each student researches and presents a paper on a topical engineering-related public policy issue. The paper is advised and reviewed by both the WISE FMR (faculty member in residence) and by the sponsoring societies, which include ASME, the National Science Foundation (NSF), The Institute of Electrical and Electronics Engineers (IEEE), the Society of Automotive Engineers (SAE), and several other professional organizations.

Executive Summary

Questions are being raised abundantly about the fitness of the supply in our science and technology workforce pipeline. Indeed, there is some sentiment within the community that there are increasing quality and potentially quantity shortfalls in the pool of scientists and engineers. This is particularly troubling at the nanoscale since nanotechnology is seen as an enabler for future growth; challenges in the pipeline could prove threatening to American competitiveness.

By examining the present status of specific trends in nanotechnology and overall trends in science and technology, a current assessment of the nano-arena is made and a prospectus for future growth in the field is formulated. Nanotechnology has several unique characteristics that set it apart from other heavily hyped trends. It first must be

pointed out that the drive for nanoscale devices comes from two directions. Bottom-up nanoscale engineers are using new advances in scanning tunneling microscopes, lithography, and lasers to manipulate single atoms to create nano-devices: super materials, molecular self-assemblers, pharmaceuticals, et cetera. Yet, as engineers develop terabyte hard drives and non-intrusive medical implants, the size scale is ultimately reaching a tenth of a micron, crossing the threshold of inter-atomic interactions and by default entering the nano regime. The presence of both a market-pull and technology-push ensures there will be at least some successes, with the intersection creating the potential for nano boom.

The high level of investment also is accelerating the development of nanotechnology. Today's adage says that research funding either lies in the biomedical arena, in information technologies, or at the nanoscale. Realizing that this large amount of funding is priming the technology, that the ability to work at the nanoscale creates new opportunities, and that as previously mentioned, everyday technologies are reaching the nano level, numerous start-ups dedicated to strictly developing nanoscale intellectual property have arisen. Unlike the recent Internet start-up craze, these investors are jumping in less than five years after the formation of the National Nanotechnology Initiative (NNI), not twenty-five years after the development of a specific military application. The field is being rapidly enabled; will America have the workforce to take advantage of this opportunity? Indeed, the unique characteristics that allow us to work at the molecular level and enjoy the benefits of nanotechnology also expose a potential lack of knowledge that could cause of harmful workforce shortfall.

Currently, the need for nanotechnology workers, perceived by some to be high, by critics to be small because the field is still developing, is for MS/PhD level researchers and for technicians (nano tool and die workers, lithographers, etc.) America, widely believed to be the world's leader at the nanoscale, enjoys its success from the leadership and industry-government-academic partnerships created by the NNI and its affiliated programs. Pockets of success lie around the five National Nanofabrication Users Network (NNUN) centers, and in areas with a strong hi-tech workforce.

Yet, that is also part of the potential problem; these are individual pockets, not broadly available opportunities. People whose work and training lies in between the researchers and technicians will ultimately become the workforce of the nano generation. We must carefully examine and question whether we have the mechanisms and depth to adequately fill the workforce pipeline.

Speaking with various nano start-ups and leaders in government, industry, and academia, there seems to be two interrelated yet distinct ways we can have a strong nanotechnology workforce. The first method is being in an area that has a workforce with a strong scientific and technical orientation. Obviously not every area is as inherently hi-tech as Silicon Valley or northern Virginia, so efforts to build a broadly educated science and technology populous must begin at the K12 level. A correlation exists between students needing remedial work in science and mathematics and an aversion to engineering disciplines in college, immediately eliminating a large chunk of potential engineers, let alone those who work at the nanoscale. The supply of (nano)engineers can also be addressed by fully involving everyone. The only scientific and technical fields that did not see a decrease in enrollment over the past fifteen years were those that had increased participation by women and minorities, fields such as psychology and the biological sciences.

The second method is developing a broad base with a working understanding of nanotechnology. In developing a broad base, the role of partnerships is vital. In an NNUN center, state funding has been used in conjunction with the federal center to have a major research university offer work with community colleges to offer a degree in nanofabrication manufacturing technology. Government laboratories and agencies can work with universities to fund research that leverages the pool of graduate students. Perhaps the most valuable characteristics of partnerships is that they can lead to the synthesizing of science and engineering, giving the skills required to succeed in this interdisciplinary field and building a strong overall scientific and technical base. Even at a more rudimentary level, students must become familiar with the concepts of moving molecules just as they are familiar with computing techniques, thus fulfilling what is perhaps called the stealth need and an area where executives in the nano arena project as a rapidly expanding area, non-technical persons with a familiarity in nanoscale concepts. Again, this can partially be addressed through partnerships; those between high schools and universities that allow students to use interactive educational tools that otherwise would be too costly to access.

Altruistic and economic arguments can be made to illustrate the importance of nanotechnology. The eye-catching nature (both scientifically/technically and the level of funding) of nanotechnology has led to speculation that it can inspire a new wave of engineers, as the space race and advent of computers did in the past. The use of nanotechnology in education could help halt the decline in the number of students studying engineering and increase American representation at the graduate level. Yet, the need to fully utilize and assure preparation in the workforce also has future growth implications. Though it touches both old and novel technologies, nanotechnology represents a new set of skills and challenges. Shortfalls in the workforce could hamper the deployment of these technologies.

Other nations are investing heavily in certain sectors of nanotechnology, some areas will succeed, and others will fail. America is fortunate to have a relatively diverse portfolio, so we should be poised for some presumable successes. Thus, we must ask and carefully answer whether we can fill the workforce pipeline to enable these successes.

Introduction

Is this science fiction? Ultra lightweight materials thinner than hair and stronger than steel. Non-intrusive cancer treatment molecules enter the bloodstream, intelligently finding and attacking the malignant cells. A hard drive smaller than a dime holds more data than the stacks of the Library of Congress. This is reality, being made possible by an emerging field so interdisciplinary that it could make other innovations such as computers or airplanes seem small and one-dimensional. Actually, this new trend, nanotechnology, is smaller than anything we have ever seen, literally a thousand times smaller than what is now known as micro.[*] According to M.C. Roco, chair of the National Science Foundation's (NSF) directorate on the nanosciences, nanotechnology is defined as "the ability to work at the molecular level, atom by atom, to create large structures with fundamentally new properties and functions." Having a working understanding of atomic structures is "leading to unprecedented understanding and control over the basic building blocks and properties of all natural and man-made things," says Roco, making these science fiction-like ideas an engineering challenge rather than a fantasy.

It is interesting to note some fundamental differences between nanotechnology and the trend of miniaturization that has swept through technology over the last half century. Albert Pisano, Professor of Mechanical Engineering and FANUC Chair of Mechanical Systems at the University of California at Berkeley, traces the lineage of micro-electro mechanical systems (MEMS) back through the development of mechatronics and micro-electronics from the mechanical relay. (2) The common characteristic between MEMS, mechatronics, and microelectronics has been the drive to

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[*] The prefix nano means 10^{-9} and micro means 10^{-6}. For reference, other familiar prefixes include kilo (10^{3}), giga (10^{9}), and centi (10^{-2}).

miniaturize mechanical systems, eventually down to the size of transistors. Nanotechnology's basis lies in a totally different principle, rather than trying to miniaturize MEMS, it attempts build mechanical and electrical systems at the molecular level.[+] Pisano says that the true power of nanotechnology is not just in the size scale, but also in the concept of molecular assembly, both manipulating atom by atom and attempts at self-assembly.

Another fundamental difference requires some understanding of quantum physics. James Murday, superintendent of the chemistry division at the Naval Research Laboratory in Washington, DC, says that when reaching sizes of 10 nanometers (a tenth of a micron), intermolecular effects come into play, considerations that usually did not need to be made by engineers working on MEMS. Even the knowledge of particle physicists is challenged when entering this regime since one atom, rather than the root mean square value of one hundred atoms, is being studied, adding a whole new set of challenges to efforts to make things smaller. (3) Thus, attempting to reach the nanoscale is not the typical order of magnitude decrease in size and increase in performance that is described by Moore's Law.[*]

An Imminent Nanoworld

The nanotechnology field is charging ahead with great speed and promise. Most researchers attribute the National Nanotechnology Initiative (NNI) with making America

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[+] Two approaches to building integrated electro-mechanical nano-systems exist. *Top-down* nanotechnology attempts to shrink into the nano regime, where devices are not only an order of magnitude smaller but also where atomic interactions must be considered. Most data storage applications are being developed through top-down research. *Bottom-up* nanotechnology attempts to assemble molecules to perform a function. An example here is a molecular switch or the carbon nano-tube.

[*] Intel's Processor Hall of Fame (http://www.intel.com/intel/museum/25anniv/hof/moore.htm) says that computing power doubles every 18-24 months, as observed by Gordon Moore (e.g. Moore's Law). The increase in performance is partially made possible by a greater aerial density. Thus, separation between data storage heads is approaching the order of magnitude of ten nanometers.

the leader in the nanosciences and strengthening our intellectual foundation in this new area. Several years ago, K. Eric Drexler, the recipient of the first graduate degree based on nanoscale research at MIT, said, "...nanotechnology will become an experimental applied science, and then mature into a branch of engineering. Today, however, it is chiefly a theoretical applied science....theoretical applied science does not have the prestige of pure science because it is concerned with building things that are useful to people, nor does it have the near-term economic value of experimental science, because it studies systems that cannot be built quite yet." (4) It is a tribute to NNI and visionaries like M.C. Roco who have been able to overcome these classic challenges described by Drexler to bring the nanosciences to the brink of the mainstream. Under Roco's leadership, the National Science and Technology Council (NSTC) Subcommittee on Nanoscale, Science, Engineering, and Technology (NSET) has focused our nanoscale research and development strategy across five areas: fundamental research, Grand Challenges, centers and networks of excellence, research infrastructure, and ethical, legal, and social implications of workforce programs. (5) The National Science Foundation believes "to capitalize on this opportunity advances in fundamental knowledge, innovation, and technique must be made before any practical benefits can be realized." (6) A break down of funding into the nanosciences is in the following table. Note the upward ramping of our levels of federal investment in nanosciences, indicating policy makers view nanotechnology as a field with much promise and is thus worthy of a large investment so the "practical benefits" the National Science Foundation alludes to can be realized.

Table 1 – America’s Federal Investment in Nanotechnology

	FY 2000 Actual	FY 2001 Estimate	FY 2002 Budget	Change ($)	Change (%)
National Science Foundation	97	150	174	24	16.1
Defense	70	110	133	23	20.9
Energy	58	93	97	4	4.3
NASA	5	20	46	26	130.0
Commerce	8	10	18	8	75.0
National Institute of Health	32	39	45	6	15.4
Other (EPA, Justice)	0	0	6	6	NA
Total Nanotechnology	270	422	**519**	**97**	**23.0**

All figures in millions. Source: *AAAS Report XXVI: Research & Development FY 2002*

For a real life example of the application of this leadership to funding, Dr. Clifford Lau, Associate Director, Office of Naval Research breaks down part of the Department of Defense’s investment: 46 out of 250 total National Defense Science an Engineering Graduate (NDSEG) scholarships were for graduate research at the nanoscale, and of the 189 Multidisciplinary Research Program of theUniversity Research Initiative (MURI) projects, 17% of the $140 million portfolio focused on the nanosciences in 2000. (7) Both NDSEG and MURI projects are classified as 6.1-level basic research but have the specific goal of helping the armed services he says. Thus, it is plausible to believe that much of our investment at the nanoscale is crossing the traditional boundaries described by Drexler and racing forward through the conventional technology development model stated by NSF, simultaneously learning fundamentals, creating inventions, and refining designs. Indeed, the speed of this field can partially be attributed to the fact that the funding is priming the technology.

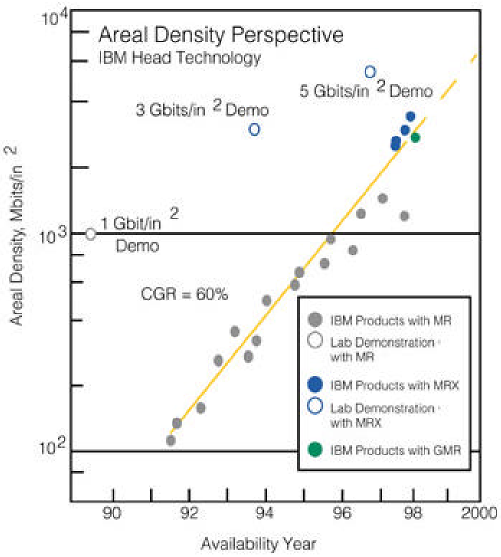
Rapidly Advancing Technology-Associated Benefits and Consequences

Application driven research abounds in various organizations. Visiting the Naval Research Laboratory, several applications of the nanosciences for the U.S. Navy including coatings, chemical/biological agent detection, thermoelectric cooling, and fuel cells can be seen in development. (3) Michael Andrews, deputy assistant secretary of the Army for Research and Technology, says “we'll see progress in the field of materials, new materials and our new Institute For Soldier Nanotechnology will focus on soldiers' uniforms.” (8) According to Andrews, it is priority for the Army “to get technologies into the marketplace so volumes will grow and prices will drop.” Yet, it must also be remembered that even with a heavily focused investment, there will naturally be a growth and development cycle, with some technologies being immediately successful, others taking a longer time to emerge and evolve, and even more never materializing.

Howard Landman has researched historical context for the Foresight Institute to predict which sectors in the nano arena will emerge first. Industries such as computers and micromechanics, which are based on bulk technologies, will see a discontinuous transition from the current process of shrinking present applications to working at the molecular level. (9) However, according to him, this transition can and probably will be made by the computer and electronic industry because they are well established and profitable despite their natural cycles (the recent dot.com crash notwithstanding). "The major strength of biotechnology is that this industry is clearly comfortable with molecules...(it) is already building nanometer-scale products in the real world, and solving real-world problems in doing so," says Landman. But he says, "chemists have the best understanding of small molecules...many profitable industries are based on chemistry, such as the pharmaceutical industry.... the real problem with this field is one of vision. Chemists think of chemistry as a branch of pure science, not as an engineering discipline...chemistry will provide the substrate for the development of nanotechnology, just as solid state physics provided the substrate for the development of the semiconductor industry." Landman's criteria for development have proven to be fairly accurate in characterizing bottom-up, or technology-pushed nanosciences. As his guidelines would predict, carbon nanotubes and molecular assemblers are still in scientific development. The Naval Research Laboratory is working on the prototype of a chemical agent detecting molecular switch, (3) and a nano transistor has just become reality, making it a question of when instead of if. The *Los Angeles Times* reports that "the unveiling on July 5, 2001 by researchers at Delft University of Technology in the Netherlands of a nano transistor that can operate at room temperature is considered to be the critical step between ideation and creation of a transistor with millions times greater computing power than today's silicon models." Indeed, the operation of the nano transistor outside of something other than a cryogenic environment means that at least in the electronics field, "a nano revolution is imminent in the coming decades." (31)

However, not all breakthroughs in nanoscience are from new technologies, or the so-called technology push. As previously mentioned, the miniaturization trend is reaching the nano domain, driving a powerful market-pull for nanotechnology. Referring to Figure 1 from Ed Grochoski of IBM's Almaden Laboratory, it is obvious that advances in data storage are rapidly leaving the micro domain and approaching the nano threshold.

Figure 1-Hard Drive Aerial Density vs. Availability Year



Yet, even though data storage is reaching this size scale due to a need to push Moore's Law rather than a mere desire to utilize nanoscale technologies, when aerial density of hard drives reaches this level, nanoscale challenges, such as atom to atom interactions, become problematic. As mainstream, everyday technologies like data storage slip into the nano regime, a whole new set of skills will be needed because the field is interdisciplinary and the challenges lie at the relatively unknown quantum level. With any emerging field, there traditionally will be initial shortages in the workforce pipeline, says Jonathan Epstein, a mechanical engineer at Idaho National Engineering and Environmental Laboratory (INEEL) and an American Welding Society Congressional Fellow in the office of Senator Jeff Bingaman (D-NM). (10)

The Army's Andrews describes the traditional technology development cycle that would lead to the rather benign[*] workforce shortage Epstein discusses. "The university laboratories have been making pretty good progress in nanoscience. And technology

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[*] Benign in the sense that the field is so new that the market place merely has not had time to reach the economic equilibrium between supply and demand.

follows science. Until you understand the science you can't move into technology efforts. You have to have equipment to allow for the fabrication of materials and devices on the nanoscale. So we have to have a good characterization before we are ready to move into the fabrication and application state," says Andrews. (8) Indeed, Pisano has a model based on his observation of fields such as aeronautics and computer science that traces the evolution of new technology and its accompanying workforce. (2) Pisano says that many new scientific trends begin when a single person, usually a professor, decides to begin investigating a new phenomenon in his lab. In the second stage, Pisano says an apprenticeship situation emerges, with the professor "tutoring" a handful of graduate students in his lab. Next, the technology shapes into products. In this step, according to Pisano, shortages are often most severe, with industry fighting over the fixed amount of graduates from the small number of laboratories. He says some workers being retrained, and other graduates setting up their own university laboratories alleviate this problem. The fourth step in Pisano's model occurs when there is enough need, pressure, and funding from government and the private sector to make the new skill part of the curriculum. Until the fourth step is reached, shortages will exist, and even attainment of the fourth step does not guarantee supply and demand equilibrium, especially if the our educational system lacks the robustness to make a rapid, dynamic response to address the new set of needs.

Table 2- Pisano's Technology Education Development Model

Step 1 **Professor Tinkers with "Invention" in Lab**	**Step 2** **Graduate Students in Lab ("Apprentices")**	**Step 3** **Invention Goes Mainstream**	**Step 4** **Due to Mainstream Demand, Standard Curriculum Built**
Low Demand **No Supply**	**Low Demand** **Low Supply**	**High Demand** **Low Supply**	**High Demand** **Increasing Supply**

An Accelerating Cycle

Yet, these new fields in the nano regime are moving rapidly; Pisano likens this to skipping from step 2 and expecting to be in step 4. Being fueled by private development is a similarity that the nano revolution bears to other fast moving trends such as the Internet revolution. California Molecular Electronics (CalMEC) is taking technologies developed by universities and using them to develop molecules that act as switches, says executive James Marek. (11) What is truly interesting here is that this start-up is dramatically shortening the technology transfer bridge between academia and industry. Because California Molecular Electronics' mission is to create intellectual property that can be licensed to other companies, development of technology is their primary focus and their primary means of generating revenue, not an afterthought limited to the domain of a corporation's research wing. Today's research could very quickly be licensed out to create tomorrow's product. Indeed, Marek says that California Molecular Electronics already has designed two switch architectures and is in negotiations with a "major cell phone manufacturer" for licensing. Because of California Molecular Electronics and numerous other start-ups focusing exclusively on the creation of intellectual property rather than also a marketable product, and because of the large amount of money previously discussed being placed into nanotechnology, the normal development cycle for new technologies has been perturbed.[*] Furthermore, it must again be remembered that many established technologies are reaching into the nanoscale. Rocky Angeluccio,

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[*] The traditional model for new technology development involves a linear progression of steps: basic research, applied research, development, production, and sales/marketing. Yet in nanotechnology, unlike in even so-called booms such as the Internet, private investors and entrepreneurs are augmenting government funding with the goal of product development immediately from the start, rather than decades after its initial creation for a narrow military application.

technical liaison, for Texas-based Zyvex Corporation, which as the brainchild of the legendary Jim VonEhr has the distinction of the world's first nanotechnology startup, likens the convergence of top-down nanotechnology (for example, data storage) with bottom-up developments (nano transistors) to the convergence of the Transcontinental Railroad. The two modes are not competing against each other as much as they are reaching a common technique. Indeed, following Angeluccio's example, we may not be at Promontory Point yet, but with the speed of new technologies and the simultaneous need to push old technologies into the nano regime, we seem to be approaching Utah!

Attainment of our goals in nanotechnology requires an increase in the number of workers, as well as the creation of a new type of worker says Angeluccio. He claims that Zyvex needs a 50% to 100% increase in the size of its workforce (currently 38 employees) to fully achieve its goals of moving from nanotechnology molecular research to application and prototype development. As they seek this goal, he says Zyvex's hiring focus has shifted from strictly researchers to people who are equally strong in traditional academic basic research and in application driven development. Because the field is so interdisciplinary, he says their employees meeting these qualifications have come from all branches of science and engineering, from electrical engineering to chemistry to mechanical engineering to physics. In the groundbreaking paper "Education and Training of the Nanotechnology Workforce," Steven Fonash of The Pennsylvania State University predicts the juxtaposition of disciplines that Angeluccio alludes to. "The implication of the ever-widening impact of nanotechnology is that the workforce must have a broad background encompassing an understanding of the principles of biology, physics, and chemistry as well as encompassing the engineering principles of design, process control, and yield," writes Fonash. He says bottom-up nanofabrication is based on basic biological processes. Knowledge of quantum mechanics and atomic force probes is essential at the nanoscale and traditionally falls in the domain of physics, and nanotechnology shares the base of manipulating molecules with chemistry Fonash writes. Perhaps most importantly, he claims mass production and economic feasibility is an engineering function.

The potential for outstripping of supply by demand seems particularly threatening in this non-traditional field, where few individual skills allow for interdisciplinary retraining to adequately patch this deficiency, perhaps not even in the short term. Roco and William Bainbridge of the National Science Foundation argue that "under present conditions far too few good students are attracted to the fields relevant to nanotechnology…to some extent, this problem faced by all the sciences, but the problem is particularly acute for nanotechnology because a very large, number of talented scientists, engineers, and technicians will be needed to build the nanotechnology industries of the future, and these professionals will require an interdisciplinary perspective." (5) Indeed, the fact that future development of everyday technologies such as data storage and semi-conductors depend on the ability to master the nanoscale means that a heavy shortage in the workforce pipeline puts not only innovation of future products and technologies by companies like Zyvex at risk but threatens the future competitiveness of today's critical sectors. Thus, the problems in the workforce pipeline can be looked at from two angles. From an outsider's viewpoint, we must address these challenges to ensure that America's economy can continue to thrive when nanotechnology merges with everyday technologies, as in the aforementioned cases. Yet, from an insider's viewpoint, we must tackle these problems so nanotechnology can reach its full potential. As Avram Bar-Cohen, executive director of the Center for the Development of Technological Leadership at the University of Minnesota, states, "until this imbalance is redressed, it will be difficult to move quickly from 'nano-fiction' to 'nano-products.' Neither the funding agencies nor the American people have the patience to wait out the 'classical' 50-year Schumpter cycles (from scientific concept to successful product), in this era of instant gratification. Consequently, we need to find ways to educate the design engineers about nanoscience/technology and provide them with a 'learning environment' within which to develop preliminary products or processes using nanotechnology."

Twin Drivers of the Potential Workforce Challenge

It is rather ironic that the breadth of demand is not fulfilled for nanoscale engineers created by the interdisciplinary nature of this field partially because of a narrow perception of what nanotechnology entails. Even though nanotechnology touches everything from materials to medicine, many people still hold the perception that the field is inextricably tied to its roots in microelectronics says Fonash. Indeed, he claims that some people are scared off of careers there and subsequently in nanotechnology because of its "boom-or-bust" nature. Fonash writes of the need to assuage these fears and generate interest in nanotechnology by making it understood that the field is no longer strictly dominated by microelectronics and stretches into biomedicine and opto-electronics and up to MEMS and micro-fluids.

Yet, what exactly we are examining must be placed into perspective before we pontificate about the need for nanoengineers. Murday makes the valuable clarification that terms like *nano*technology and *nano*sciences simply refer to a size scale on the order of a tenth of a micron. (3) Thus, many of the social, economic, and ethical challenges facing engineers working on the stamping of metal for example, will parallel the challenges that engineers working on nanoscale hard drives will face. Murday believes that we will not have nanoengineers* per se, but rather mechanical engineers using nanotools to work at the nanoscale, just as mechanical engineers use computers to work on computations. However, safely engineering in the sub-micron regime does require greater understanding of molecular phenomena, thus the nanoscale is a new discipline different from anything we have known before because it does present new technical challenges to accompany the old social, economic, and ethical questions. The nano workforce parallels this paradox of being just a size scale and a whole new field. We do not always have enough suitable engineers (a long running problem) regardless of the size scale, but there are not many educational opportunities to gain competency in the nano regime (an issue that the leaders of NNI and its spin-offs must address). The workforce pipeline challenge, both now and projected, can be traced to two things: an overall lack of engineers and physical scientists in America, and not fully addressing the educational needs at the nanoscale.

An American S&T Crisis

"Personnel skilled in math, sciences and engineering are in short supply in all technology-based industries," says Gayle C. White, Chairman of the National Defense Industrial Association's Space Committee. (12) Paula Collins, government relations representative for Texas Instruments, agrees, saying that there are simply not enough

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* In this specific case, I am using the term nanoengineer to represent the concept of an engineer trained in a specific discipline: chemical engineer trained in chemical engineering, nanoengineer trained in nanoengineering, etc. Throughout the rest of the paper, the term is much more generic, referring to an engineer, regardless of discipline, whose work is done in the nano regime.

engineers. (13) While she says that making lucrative offers to electrical engineers that they are trying to recruit can help, ultimately she compares this to “robbing Peter to pay Paul,” with Texas Instruments taking workers away from other companies.

Figure 2 – from *NSF S&E Indicators 2000*

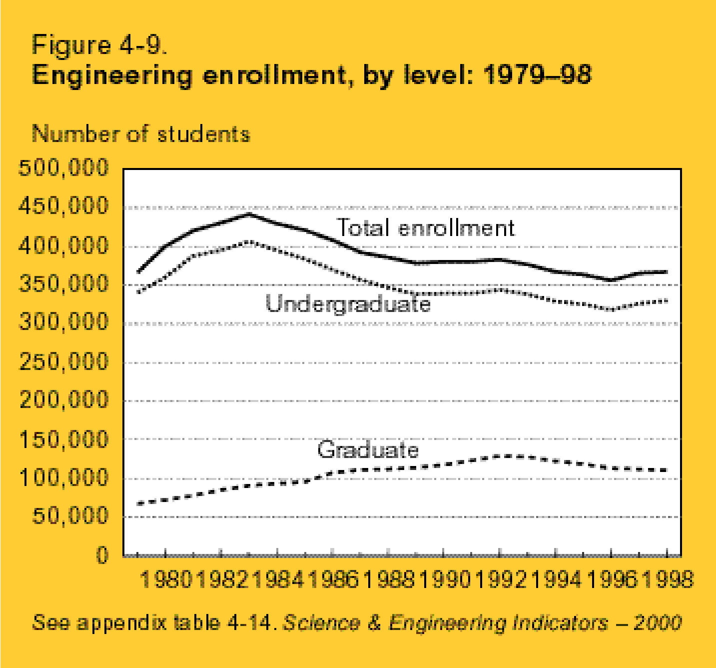

Figure 4-9.
Engineering enrollment, by level: 1979–98

See appendix table 4-14. *Science & Engineering Indicators – 2000*

According to the NSF’s *S&E Indicators 2000* report (14), “in the past two decades, the U.S. college-age population declined by more than 21 percent—from 21.6 million in 1980 to 17.0 million in the year 2000…echoing this overall demographic decline, the number of students enrolling in undergraduate engineering decreased by 16 percent, from a high point of 441,200 students in 1983 to 356,000 in 1996.” Clearly, part of this decline and accompanying challenge in workforce supply is simply a function of demographics rather than an indictment of policy towards science and engineering education. Nevertheless, as the economy continues to acquire a more hi-tech orientation, technically educated workers will be at a premium, with shortages regardless of cause, placing America at a disadvantage. Looking to demographics, there is cause for optimism for a natural upswing in the number of degrees awarded, similar to the natural decline; the NSF predicts that “the college-age population decline reverses itself in the year 2001…and increases to 19.3 million by the year 2010…a 13-percent increase over the year 2000 figure.” But, with other nations ramping up their efforts to increase the inflow into their science and engineering workforce pipelines, merely waiting for this natural increase may not be sufficient.[*] Furthermore, there are distress signs. While other nations are furiously working to improve their education in science, technology, and engineering, standardized test scores show the rudimentary problems America faces. Though it would be spurious to suggest that the comparatively weaker elementary and secondary mathematics and science education infrastructure means that America will not be able to extend its fifty-year trend of 5% (see footnote), there also is little reason to believe that enrollment in science and engineering will increase to keep pace with other nations and to fulfill the increased long-term need for technically trained workers across the board. Studies by the Bureau of Labor Statistics indicate potential outstripping of supply by demand; “overall engineering employment is expected to increase as fast as the average for all occupations, while the number of engineering degrees granted has remained fairly constant over the past several years.” The report also indicates growth in the need for engineering technicians. (32)

The relative downturn in Americans pursuing engineering degrees and physical sciences degrees is hitting government extremely hard. White tells a shocking story based on a General Accounting Office report indicating how this shortage is hindering

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[*] At any give time since 1950, approximately 5% of all 24-year-old American persons (with and without degrees) have held science and engineering degrees. (14) By contrast, in the past twenty-five years alone, Taiwan, Germany, South Korea, and the United Kingdom have increased their proportions from 2 percent to 7, 8, 9, and 9 percent respectively.

both the safety and future of certain programs at NASA. (12) "GAO indicated that NASA had identified 30 areas at the Kennedy Space Center that do not have enough staff to meet required backup coverage. This workforce shortage has forced NASA to use personnel lacking in experience level and training to perform required safety inspections. Furthermore, (GAO) noted that throughout the Office of Space Flight, there are more than twice the number of workers over 60 years of age than under 30 years of age. This jeopardizes the program's ability to 'hand off' leadership roles to the next generation."

Some people argue that with the end of the Cold War and the subsequent decrease in emphasis on space innovation have hindered graduates' desire to work at places like NASA. Even White admits that, "in today's workforce, bright young graduates frequently seek positions where personal growth is available over jobs where stability is offered." White's theory makes perfect sense when explaining why many young engineers were attracted to Silicon Valley in the late 1990's. Yet, it is open to more debate when applied to an institution like the Naval Research Laboratory, that despite having had some ups and downs in funding in the recent past, is producing some of the finest nanotechnology research in the world; research on molecular switches for detecting biological and chemical warfare agents that Murday honestly believes will result in a Nobel Prize. (3) Despite its leadership in the field, the laboratory has encountered problems finding qualified American Ph.D. recipients to work in the nanotechnology department. Murday says that NRL has a unique niche in the science and technology community since it seeks to bridge academic with applied research to develop innovations for the Navy. Thus, he says its best researchers have come from those who want a cross between the freedom offered from academic careers and the pay associated with corporate laboratories. However, the recent downturn in the number of students pursuing R&D careers has hindered NRL's recruiting, prompting programs that allows NRL (and other governmental institutions) to have slightly more flexibility in compensating researchers. Nevertheless, Murday says that government salaries are traditionally less than those offered by private laboratories, and universities have increased both their pay and hiring, making it hard for NRL to compete in the smaller labor pool.

In some ways, because funding for the nanosciences often comes from reprogrammed dollars, retraining workers and sharing research faculty can temporarily bandage the problem. Much of NNI is reprogrammed money, as are NRL's expenditures in the nanosciences, so theoretically the amount of workers needed should be no more severe than what is currently needed for macro and micro projects. Indeed, NRL's new low-noise, ultra hi-tech building to house their Nanoscience Institute will be staffed by researchers from current departments. (3)

Yet reprogramming has numerous side effects that are undesirable, even if it comes from fields seen as dormant. For example, as the influence of the golden troika of nanotechnology, health care, and information technology continues to increase, the aerospace field has fallen on harder times recently. Heidi Wood, Morgan Stanley Aerospace/Defense Analyst says that in 1980, the aerospace and defense sector had an S&P 500 market cap of 2.4% before falling to 1.8% in 1990, and 0.9% in 2001. (15) Wood adds that the aerospace industry has been downgraded in the view of investors from "hi technology" to a "basic industry." Indeed, this basic industry has underperformed on Wall Street, Wood says its stocks fell 52% percent in 1999, the watershed year for the bull market! Stopping short of picking winner and losers, it is tempting to argue for reprogramming of money into nanotechnology, especially from the DoD budget. While this could help us stay ahead in the competitive nano-world and might seem logical considering the shrinking influence of the aerospace sector, the overall drought of workers in science and technology is so severe, reprogramming might instead be the final nail in the coffin of some struggling sectors of S&T, such as the aforementioned NASA.

The NASA example is an extreme case. Again, while it is not and should not be our policy to use funding to pick winners and losers (Robert Cannon, senior counsel of the Federal Communications Commission Office of Plans and Policy, cites the flops of Japan's investment in wireless internet and France's ISDN when governments pick winners and losers (16)), funding presumably could be redirected from certain low-growth, low-tech, self-sustaining industries into hi-risk, hi-tech, cutting edge technologies such as research at the nanoscale. Nevertheless, even if in some cases that is a viable solution, it will only solve part of the problem, because there is a serious challenge in attracting workers. This is not strictly a case of a place such as NRL not having the funding to reach the intersection of the supply and demand curve. There are challenges in the workforce pipeline, and they threaten our research and development infrastructure.

From Stanley Williams' experience in hiring for Hewlett Packard Laboratories, he says that there are hard challenges in finding American scientists and engineers. (30) According to Williams, an HPL Fellow and the Director of Quantum Science Research at the Palo Alto center, "it turns out that no one in my group under the age of 45 was born in the US, and several received all of their degrees abroad as well. In terms of the worldwide market, I can always find qualified people if I am willing to recruit in China or Russia (which I have). However, I don't think that we can rely on a steady supply of foreign brains to create such a crucial new technology for the US." Indeed, Williams fears do have justification, especially as nations such as China continue to develop. According to NSF data, "the stay rates (overall 53%) are higher for scientists and engineers from developing countries such as China (92 percent) and India (83 percent). In contrast, stay rates are lower for those from emerging economies such as Taiwan (36 percent) and Korea (9 percent) that can absorb highly qualified, skilled scientists and engineers." It is troubling to wonder what will happen if China or India follow the trends in Taiwan or Korea.

Education Not Fully Addressing the Needs of the Future

According to Professor Supriyo Bandyopadhyay, director of the Quantum Devices Laboratory at the University of Nebraska at Lincoln, there are difficulties finding faculty members in nanotechnology. (17) Even though top-notch universities such as UC-Berkeley have talented faculty members like Albert Pisano and Arunava Majumdar leading their efforts at the nanoscale, this distribution does not always extend down through all Research I universities, let alone smaller colleges, making it difficult to fill the workforce pipeline.

The Quantum Devices Laboratory at the University of Nebraska in Lincoln is typical of many university nano-centers. Professor Bandyopadhyay says that his lab has produced approximately one dozen graduate degrees and four post-docs. According to Bandyopadhyay, the students' backgrounds are primarily in electrical engineering and physics, and upon graduation, they have gone into research positions with Motorola, Raytheon, and NASA, with one Ph.D. becoming a professor.

Indeed, this lab in land of the Cornhuskers epitomizes what is right and what is wrong with America's nano-field. Students with undergraduate degrees in physics and engineering are obtaining a graduate education focused on basic nanoscience rather than nanotechnology. Most are then going into industry research and development positions to further our knowledge of applications of nanotechnology. In that sense, many of the objectives of NNI appear to be realized. However, the lab has produced 12 master and doctorate degrees. Only one graduate of the Quantum Devices Laboratory is starting his own lab at another university. Similar statistics can be found at Pisano's laboratory in Berkeley. Currently, the plurality of Pisano's students are filling the small but intense need of small companies and start-ups. (18) The rest are going into large laboratories, with an even smaller number becoming professors. Without even considering lab start-up times and the number of graduate students he will initially attract, generating students at this rate will neither fill the need for nano-engineers now, nor if the field booms in five to ten years as projected.

The start-up California Molecular Electronics focuses on research, so executive James Marek says that it has not experienced severe staffing shortages since the main characteristic they look for is basic knowledge of materials and an ability to work on molecules. (11) The former can be found in most Ph.D. chemists, and latter skill is often acquired on post-docs. Marek believes that California Molecular Electronics will remain comparatively small due its emphasis on research only, but he does expect to hire physicists and electrical engineers in the near future, with mechanical engineers coming on board in the slightly more distant future. Will they encounter staffing problems due to economic constraints imposed by the limited supply of electrical engineers? Will there even be mechanical engineers (or even more generically engineers who fill the role of building systems) trained in the nanoscale since even the more heavily engineering oriented nano programs like the one at University of Nebraska at Lincoln or the University of Washington* have strong electronics focuses?

Right now, there is very little clear undergraduate curriculum that leads to a career in the nanosciences. Kenny Jow, an undergraduate materials engineering student at MIT, learned about the nanoscale from his own readings and combined that with his basic knowledge of materials to build prototypes of carbon nanotubes on his internship at the start-up NanoLab, Inc. (19)

Currently on Par, Warning Ahead

Everyone interviewed subscribes to the consensus that America currently leads the world in nanosciences and nanotechnology. Henry I. Smith, Keithley Professor of Electrical Engineering at the Massachusetts Institute of Technology, goes to as far as commenting, “no need to discuss with me. I don't think there is any problem. I don't anticipate any shortage. Business as usual is fine. No need to panic or do anything different. Any problems with our education system are unrelated to nanotechnology.” (20) Indeed, Steven Fonash, director of the Penn State Nanofabrication Facility, makes the valuable clarification that *right now*, the need for workers in nanotechnology lays in two areas, nanofabrication technicians, and researchers. (21) However, industry says that

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* The University of Washinton’s Center of Nanotechnology (nano.washington.edu) is amongst the original nano research centers at American universities. It offers dual graduate degrees in nanotechnology with electrical engineering, physics, and in various other disciplines related to biology, chemistry, and/or materials.

in addition to today's need for technicians and Ph.D. level researchers, there will be a need for design engineers.

A fundamental lack of understanding exists in the nanosciences, there is both ignorance and misunderstanding. Fonash writes that "secondary school students have grown up around computers at every turn and are bombarded with talk of the information age but do not know anything about nanotechnology…(they) are at home with the concept of moving information electronically but are not at home with the concept of literally moving molecules around to create and build." This ignorance impedes the development of a nanotechnology workforce; Fonash claims the "basic ingredient" is to developing this workforce is having students, teachers, and even parents aware of nanotechnology's rapidly expanding impact on an array of diverse fields. Exactly how well this need is filled, both now and in the future is a nebulous question.

According to human resources director Terry Mehr, Asylum Research is typical of other nano startups on the West Coast in that they are bracing for large growth in the near future. Nano-instrumentation tools like the ones they manufacture will become mainstream as diverse industries such as polymers, pharmaceuticals, and semi-conductors continue to get smaller, reaching the point where quantum effects come into play. (22) Asylum Research currently is able to fulfill most of their staffing needs; Mehr says that they are receiving dozens of resumes for R&D positions and have had few problems training people with traditional backgrounds in mechanical or electrical engineering to work as production technicians in their firm. Asylum Systems has benefited from the influx of graduates of University of California at Santa Barbara who have experience in National Nanofabrication Users Network (NNUN) center on campus and from workers formerly at Digital who are tremendously skilled in instrumentation and electronics and can easily transition into specific parts of the nano arena.

However, Mehr says that Asylum Research has had difficulties finding technical sales staff and interns for their engineering program. Indeed, with limited industry experience to fall back on and little basic education in the nanosciences, a hole forms in the middle ground, below the researchers and above the technicians. Other factors also mitigate Asylum Research's success in staffing. They employ approximately 20 employees, and have been fortunate enough to find what Mehr calls "gems, the best of the best from universities." Yet, Mehr also notes that they have not had a lot of success finding more typical students in universities. The depth of talent in the nano-pool may be thin; ambitious start-ups in traditionally hi-tech areas and/or in close proximity to one of the five NNUN facilities may enjoy great success, but when a larger corporation is looking to work at the nanoscale, it may not be as lucky in finding both the quality or volume of workers, limiting our ability to compete in the mainstream market in the near future.

The comments of several leaders in nanotechnology indicate that skills associated with mechanical engineering such as design and fabrication will be in high demand as the nano field evolves. Jonathan Epstein of INEEL and a fellow in Senator Bingaman's office projects mechanical engineers playing a larger role in the interdisciplinary world of nanotechnology. (10) As we move towards actual products, Epstein says that mechanical engineers will work with the physicists, chemists, and electrical engineers who currently dominate the research and prototyping in the field. Jim Chavez, an ASME Congressional Fellow in Representative Heather Wilson's (R-NM) office and an S&E policy advisor at

Sandia National Laboratory, also projects a large increase in the influence mechanical engineers will exert over the nanosciences. (23) He says that the advantage of mechanical engineering is its integration of broad skills. As the nano applications go mainstream, the broad range of skills that mechanical engineers possess will place them in demand in the interdisciplinary nano world.

Pisano is more blunt, saying “I triple-emphasize…that what's missing are people who know how to DESIGN things at the micro and nanoscale. The efforts of private industry to create low-level nanoengineers cannot address that lack of designers. That is the essential problem. And THAT is the direction in which the proposed ASME Nanotechnology Institute series of webcast courses should be focused. The DESIGN of such systems.” (18)

It must be pointed out that if mechanical engineering figures to play a prominent role in nanotechnology, there is some good news on the horizon for education there. Arun Majumdar at the University of California in Berkeley runs a nanotechnology program based solely in mechanical engineering. While the laboratory has produced only three nano-ME’s, two of them have taken academic positions, with the other now working for a biochip company.

Fonash says that a deficiency in nanotechnology workforce would “grow out of a shortage of perspective” since the cutting edge research encompasses chemistry, biology, microelectronics, and many other fields. (21) Pisano’s Berkeley colleague Majumdar traces the root of shortages in the nanotechnology workforce to two unique characteristics, saying, “it is hard to separate a problem into traditional discipline…(and) one needs to know both the science and the engineering to make any contribution.”

Majumdar predicts “there will be a shortage of people who have a working knowledge of multiple disciplines and yet specialize in one…these may be design engineers.” (33) Yet, regardless of today’s situation or the root of this issue, workforce problems could lie ahead; Pisano is adamant in his belief that “once nano goes mainstream, yes, indeed, there will be a total outstripping of supply by the huge demand.” (18)

Correcting the Workforce Issue

It seems clear that an interdisciplinary background is needed to excel in nanotechnology. Whether we are trying to develop technicians, engineers, or researchers, education will reign supreme in the new nano age, where people with both breadth and depth of knowledge are in an advantageous position. “The shortage will be people who do not see the boundary between science and engineering and are equally comfortable and capable of working in both,” says Majumdar. (33) There is some sentiment for the creation of a degree in nanotechnology or nanoscience, much like the computer science and computer engineering curriculum was created a quarter of a century ago. Yet, at this time, a degree in nanotechnology has only lukewarm support from many leaders in the field. According to Murday, it is better to have a strong background in a classical field such as aerospace engineering or chemistry that is supplemented by a few basic courses in the techniques used at the nanoscale (much in the way computers are part of today’s mechanical engineering curriculum). (3) Because the nano field is so interdisciplinary, Murday fears that an undergraduate degree in nanotechnology will not have enough depth.

In studying the concepts of K. Eric Drexler, Lenhert has summarized the skills requisite for the emerging nanotechnology workforce. He writes that this workforce will have a proficiency in designing and building functional devices that is derived from a core knowledge of the workings of biological compounds and of computer modeling and simulation of atoms. This base is achieved by coursework in calculus and physics, applied to the areas of thermodynamics, quantum mechanics, electromagnetism, and molecular behaviors such as vibrations, deformations, and transformation. (34)

From interviews, there is much broader support in the science and technology community for integration of nanotechnology into inter-disciplinary curricula. Indeed, the integration of this curricula into various fields maintains the spirit of the application of nanosciences; Michael Reischman, Special Assistant to the Associate Administrator in the Office of Aerospace Technology at the National Aeronautics and Space Administration (NASA), agrees with Murday and Marek, saying that the true power of nanotechnology comes when it is combined with other technologies and used as an enabler for future growth. (24) However, some like California Molecular Electronics' Marek believe that the interdisciplinary curriculum will "inevitably" grow into a major in its own right. (11)

Regardless of if and when some type of a nanotechnology is initiated, both the current workforce pipeline challenges in the science community and the projected challenges in the nano arena must be addressed. Two interesting models are NASA's Office of Aerospace Technology's (OAT) University Research, Engineering and Technology Institutes (URETI) and the associate's degree offered at The Pennsylvania State University in nanofabrication manufacturing technology.

URETI is the type of program that could be the model for simultaneous research and teaching in nanotechnology. Indeed, this program's three principal areas are all nano-related: biologically-inspired and nanotechnology enabled aerospace structural materials, bio-nanotechnology for advanced electronics and computing, and fundamental opportunities across bio-nano-information technology. The strategy of URETI is inherently interdisciplinary , with objectives including: “1. A guiding vision and plan to research and exploit innovative and emerging opportunities in research and technology that can have a revolutionary impact on future NASA missions. 2. An interdisciplinary research program promoting the synthesis of science, engineering and other disciplines. 3. Active, long-term and, mutually-beneficial partnerships with industry, non-profit labs and other universities. 4. An educational program for undergraduate and graduate students that directs students toward areas of critical interest to NASA and provides new educational opportunities for NASA personnel. 5. An array of opportunities for collaboration and connectivity to NASA Centers, including fellowships, special academic programs, technology transfer, and personnel exchanges. 6. The supporting infrastructure and management system, necessary space and enabling equipment, and university commitment to facilitate, reward and sustain the URETI activity.” Note also that “participation from HBCU's (Historically Black Colleges and Universities), OMI's (Other Minority Institutions), SDB's (Small and Disadvantaged Business), and SWOBI's (Small Women-Owned Businesses and Institutions) is highly encouraged.” (25) Hence, it simultaneously produces engineers for the nano pipeline and continues to enhance our understanding of the nanosciences, crucial twin objectives since even though a need for workers exists, the field is still young and our knowledge is still in the developmental stages.

Another model addressing the building knowledge in nanofabrication, or the practical application of nanotechnology to the manufacturing processes, is offered at the National Nanofabrication Users Network center at The Pennsylvania State University. Jeff Catchmark, associate director of the Penn State Nanofabrication Facility, says that learning process engineering is inherently time consuming. (26) Generally, corporations do this when a person is first hired into a process engineering position, but he says that this is less financially feasible in nanofabrication. With the making of products at the nanoscale (i.e. nanofabrication) connecting diverse fields such as biotechnology, electronics, and manufacturing, Catchmark fears that it may be too cross-disciplinary for a company to be able to or even expect a biologist to be trained in process engineering or for a technician to master molecular biology, forcing the need for a module of classes focused on nanotechnology.

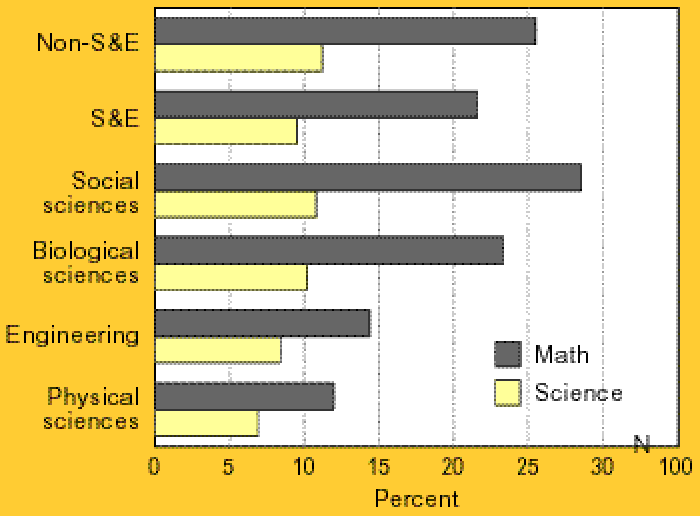
Fonash and Catchmark have successfully setup what is called the world's only associates' degree in nanofabrication manufacturing technology at The Pennsylvania State University. (21,26) He says this program takes three times a year, batches of 30 final-semester students and trains them in top-down and bottom-up fabrication techniques. According to Fonash, the semester long capstone program costs $10,000, with the Commonwealth of Pennsylvania splitting the cost with fourteen community colleges across the state. He says that the supply of workers this program produces has made Pennsylvania one of the nation's leaders in nanofabrication. Indeed, he claims graduates have received offers in excess of $50,000 from in-state powerhouses like Agere and Seagate, and the Pittsburgh start-up Xactix, which plans to hire 15 technicians in the near future. (21)

Yet, while the nanofabrication manufacturing technology degree is quite focused on training workers for employment in the field, its vision of the big picture makes it broad. Fonash says that the advantage from a worker's standpoint of a degree in nanofabrication is that it allows the person to have a broad base so they can work in any area of nanotechnology. Unlike being trained by an employer in a specific area (micro-electronics for example), he says the degree holder can work at the nanoscale in biotechnology when optics is down, and vice versa. In the spirit of that degrees' versatility, numerous advantages abound to giving students, from kindergarten through college, a broader base in science and technology.

Indeed, many believe generating interest in science in children is the line of attack to fill the workforce pipeline and to address long-term needs specifically in nanotechnology, science in general, and in whatever the next great trend may be. The S&T workforce and K12 education are inextricably linked together. The table illustrates the relationship between a high school graduates' need for remedial work and his chosen college major; a weak science and mathematics background significantly reduces the pool of potential engineering students.

Figure 3 – from *NSF S&E Indicators 2000*

Figure 4-8.
Freshmen reporting need for remedial work in science or math, by intended major: 1997



See appendix table 4-12. *Science & Engineering Indicators – 2000*

Murday says that increasing the pool of scientists and technical persons is a must since merely attempting to refocus current efforts into a field takes away from the ever thinning supply in other areas, much like the previously discussed reprogramming. He says that by teaching the nanosciences to K-12 students, not only can people understand the field, but it also can spur a trend towards the sciences since “it is sexy, it catches people’s attention,” much like the nuclear weapons and space programs did forty years ago and computers did ten years ago. Murday says tools developed by university consortia, such as the University of North Carolina’s nanoManipulator or the Arizona State University’s INVSEE, allowing high school students to manipulate atoms at the molecular level generates excitement amongst students and allows schools to have access to science teaching tools that they could not normally afford. If this model works, it is believed that the students’ new interest in technology will spark careers in engineering. (3)

Duncan Moore, Kingslake Professor of Optical Engineering at the University of Rochester and a former OSTP advisor under President Clinton, pinpoints the perceived crunch in the science and technology workforce to middle school, grades 5 through 8. (35) He says we are amongst the top nations in science for fifth graders, drop back into the middle of the pack for eighth graders, before falling to the bottom for high school juniors. Furthermore, Moore says that students often have a bad impression of science from a middle or high school experience, whether it be poor teaching, academic difficulties, or boredom, leading them to avoid any science or math courses once in college. Generating interest with tools like nanotechnology can stem this decline; if at least students have a neutral view of science going into college, Moore is confident that the excitement from areas such as nanotechnology, bioengineering, and gadget-applications like GPS can appeal to these open minded students and spark a new generation of engineers, much like the Sputnik and the subsequent space race did forty years ago. Nevertheless, implementing "technology (and engineering) with a face" into classrooms is a moot point without having K-8 teachers who are comfortable in the sciences, Moore says. Thus, making long-term changes becomes a challenge of supplying enough teachers who are comfortable (more so than knowledgeable Moore says) in sciences as it is a curriculum issue.[*] Going one step further, Moore points out that these advanced level science classes must reach the students. While Duncan Moore enthusiastically supports initiatives like INVSEE, he is concerned that in some schools with only 8% of students taking physics, even if the program influences half of the people

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[*] An interesting tangential reading topic is differential pay for teachers. Two such programs exist in Cincinnati, OH and Rochester, NY. In Rochester, Moore says that people spend part of the day teaching chemistry, mathematics, and/or physics classes, and then the rest of the day and summers working for companies like Kodak or Xerox, with both the company and school district paying the teacher/employee.

it comes into contact with, only 4% of the overall student population will be impacted, helpful but not enough to reverse the whole problem. In New York, Moore cites the example of implementing digital imaging in a photography arts class to build interest in computer technologies. Similar back-door approaches could be used to bring the nano curriculum into school districts that are limited in traditional classes like chemistry and physics.

Generating interest in math and sciences at the K12 level is "crucial to America's success in 20 years," but Reischman is adamant about the impending shortage of workers that NASA faces now. Reischman believes there are just not enough engineers with the proper match of skills to fill the needs of industry, academia, *and* government. Indeed, even proponents of better K12 science and math education like Duncan Moore admit that the benefits will not be seen until 2010 if successfully implemented today. Reischman says that to solve this problem, we need to leverage the existing brainpower of students currently in universities through programs like URETI, and provide "inspiration and motivation" for students entering universities. (24)

Incremental changes in the engineering education process could assist both the nano-world and the overall science and engineering pipeline. It is believed that improving K12 education will increase the flow into the workforce pipeline by making a larger of pool of potential candidates viable for studies in science and engineering. Yet, we must also make sure that efforts to increase the pool are not in vain. According to the NSF, the only disciplines to buck the demographic trend and see an increase in enrollment are psychology and the biological sciences. These increases are attributed to an influx of women and minorities in the field. Perhaps stronger K12 education in math and science will mean more underrepresented groups go into engineering. The entire issue is an extremely complicated socioeconomic dilemma going beyond the scope of this report, but the role of women and minorities cannot be forgotten in addressing the overall science and technology shortage and the arising problems in the nanotechnology workforce pipeline.

Issue and Solution Summary

Currently, the need for nanotechnology workers, perceived by some to be high, by critics to be small because the field is still developing, is for MS/PhD level researchers and for technicians (nano tool and die workers, lithographers, etc.) However, people whose work and training lies in between the researchers and technicians will ultimately become the workforce of the nano generation. We must carefully examine and question whether we have the mechanisms in place or in development to adequately fill the workforce pipeline.

In addressing this situation, the value of partnerships, between federal government, universities, state government, local school districts, and/or industry cannot be understated. Pockets of successes near NNUN centers where state, federal, industry, and private dollars have intersected serve as powerful evidence of this. Partnerships between schools and universities can be used to attack the root of science and technology workforce pipeline challenges and reduce ignorance about nanotechnology. Government laboratories and agencies can work with universities to fund research that leverages the pool of graduate students. Perhaps the most valuable characteristics of partnerships is that they can lead to the synthesis of science and engineering, giving the skills required to succeed in this interdisciplinary field and building an overall strong scientific and technical base.

Conclusions

While a need for a nano workforce appears to be imminent, it must remembered that this is a new field, so not every technology will be successful, just as not every dot com succeeded. Patrick Quinlan, national energy policy director for the American Council for Energy Efficient Economy and a former ASME Fellow in the Office of Science and Technology Policy under President Clinton, says that an "80-20 rule" applies to new technologies; roughly eighty percent of new innovations will flop and/or take years to develop, and twenty percent will become successful and replace existing products. (27) Murday agrees that there is some hype at the nanoscale. Indeed, the best molecular assembler (the human) takes twenty years to mature, produces large amounts of waste, and requires a large energy input; not exactly a great return on investment.

Nevertheless, nanotechnology is here and is not going away, even if some applications take longer to emerge. Michael Andrews, deputy assistant secretary of the Army for Research and Technology, agrees that in areas where the technology is evolving into the nanolevel, the impact of nanotechnology will be seen imminently. However, in areas where nanotechnology is being used to develop new technologies, the development cycle is longer he says. (8)

"In the 1800's, realization of high performance, traditional industrial machines required the development of a fundamental understanding of the microdomain. Similarly, to effectively design, build, and operate machines in the microdomain, we must have a fundamental understanding of the materials and surfaces in the nanodomain.," says Paul McWhorter, Deputy Director, Microsystems Science Technology and Components Center, Sandia National Laboratory. (28) Thus, when addressing the workforce issue and even the fundamental question of funding research and development into the nanoscale, we must ask how can America enable future growth and leadership? Testifying before Congress, Nobel Prize winning chemist and physicist Richard Smalley of Rice University states "it's particularly possible for countries that are not as well funded as the United States to be major players in this area" since "nanotechnology is intrinsically small science" so "it is a place where many small laboratories are active…in fact, hundreds throughout the world." (29) From his viewpoint in industry, Marek says Japan could quickly close the gap if they follow through with their plan match our level of funding. (11)

Our investment at the nanoscale is critical to the future of our leadership in the sciences. Citing history, Murday says that America was able to become the world's science leader in the last 50 years because while Europe and Japan were trying to rebuild their economies from World War II, America already had a strong university and research infrastructure in place. Murday has seen large advances by other nations in the last five years, as evidenced by the fact that up to half of major journal articles foreign researchers write. In his opinion, other nations' advances at the nanoscale are comparable to America's. "We're running to stay a step ahead, not a mile ahead."(3)

Nanotechnology and the nanosciences field will allow us to extend Moore's Law for another 30 years Murday says, but it will not totally replace current technologies, at least in the short-term. According to Murday, missing the nano wave will cause America to gradually fall back into the pack as old technologies phase out. However, by investing a combined $1 billion (on the order of magnitude) a year for ten years into all areas of nanoscale research, we can make strides towards remaining the leader in the new competitive world he says. With nanosciences touching materials, pharmaceuticals, and electronics, each $1 trillion (on the order of magnitude) industries, the $10 billion investment today blossoming into a multi-trillion dollar behemoth tomorrow is truly a great return on investment.

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