

A Rubric for Post-Secondary Degree Programs in Nanoscience and Nanotechnology*

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Based upon a set of 'big ideas' identified by recent workshops and a study report, a broad curriculum framework has been developed for degree programs in nanoscale science and engineering (NSE). The framework is built around four essential areas or nodes in NSE that include— Processing (how nano-entities are fabricated), Nanostructure (how the structure of nano-entities can be imaged and characterized), Properties (the resulting size-dependent and surface-related properties of nanostructured materials/devices), and Applications (how nanomaterials and nano-devices can be designed and engineered for the benefit of society), which can be abbreviated as 'P-N-P-A'. This paper argues that the P-N-P-A rubric provides a tool for program and course construction and evaluation in higher education. An analysis of emerging NSE degree programs in the US suggests that improvements need to be made in the programmatic balance among the P-N-P-A nodes, with particular attention being paid to essential features such as the interdisciplinarity of NSE and its societal impact (ethics, safety and so on). A significant challenge for achieving programmatic balance is providing students with access to advanced instrumentation, which is an essential element for student mastery of the 'nanostructure' node. Recommendations and challenges for achieving programmatic balance are discussed.

Keywords: Nanoscience; nanotechnology; curriculum design; degree programs; course design

INTRODUCTION

NANOSCIENCE AND NANOTECHNOLOGY have important precedents in both the decorative arts (e.g. the well-known Lycurgus cup from Roman times and medieval stained-glass windows) and in chemical technology (e.g. 19th-century colloids and mid-20th century catalysts). It was not until 1959 and Richard Feynman's vision of 'plenty of room at the bottom', however, that the nanoscale began to receive widespread attention [1] and Norio Taniguchi coined the term 'nanotechnology' as recently as 1974 [2]. As in other fields of science and technology, scientific instruments were enablers for the development of nanoscience/nanotechnology, namely the scanning tunneling microscope (STM), developed in 1982 [3], and the atomic force microscope (AFM), developed in 1986 [4]. For the first time, researchers could image and manipulate materials/devices at the atomic scale.

A worldwide emphasis on nanotechnology marked the opening decade of the 21st century. In 2001, President Clinton established the 'National Nanotechnology Initiative', with other nations in Asia and Europe quickly following suit. Foley and Hersam [5] cite global statistics of an eightfold increase in government spending from 1997 to a level of more than US\$4 billion in 2005, and overall spending (both public and private sectors) of US\$9 billion as of the same year. Various studies have documented the unprecedented increase in the percentage of patents that are nano-related issued during the closing years of the 20th century and opening years of the 21st century (e.g. Hullmann and Meyer [6] and Wong et al. [7]). Walsh [8] has even described nanotechnology as a 'disruptive technology', a technological innovation, product, or service that eventually overturns the existing dominant technology paradigm, using a term first introduced by Bower and Christensen [9]. Given the potential of nanotechnology, virtually all fields of science and engineering, including biology and biotechnology, are converging at the nanoscale [10].

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In spite of the unprecedented pace of developments in nanoscience/ nanotechnology, technologists and market analysts have been reasonably successful in delineating areas of commercial applications and in setting research and development agendas for various nanotech sectors [11, 12]. Government-sponsored reports have also documented the growth and development of nanotechnology worldwide, including assessments of emerging application domains [13]. There have even been early attempts at 'road-mapping' in niche areas, i.e. plotting the course for nanotechnology research and development [8].

What have been lacking in the nanoscale arena are commensurate developments in education reform. Roco estimates a need for 2 million nanotechnology workers over the coming decade to service the anticipated US\$1 trillion annual global market for nano-products [14]. While much of this workforce will come from scientists and engineers crossing over into NSE from non-nanotechnology fields, nevertheless the anticipated demand will significantly outpace the current five per cent annual growth rate in the number of jobs in the US labor force requiring science and engineering skills [5], which is already growing five times faster than the rest of the US labor force. Schummer has documented the global institutionalization of nanotechnology, i.e. that the surge in demand for trained nanoscientists and nanotechnologists is a global phenomenon of unprecedented proportions [15]. Meanwhile, experts are not sanguine about the state of nanoscience/engineering education. Foley and Hersam [5] lamented the sorry state of K-12 STEM (science, technology, engineering and math) education in the US in light of the anticipated high demand for nano-savvy workers. Jackson, former president of the American Association for the Advancement of Science, refers to the decline in US native science and engineering base as a 'quiet crisis' [16], especially given the statistical correlation between K-12 math and science scores and a country's GDP growth rates [17]. Whether as a 'disruptive' or an evolutionary technology, nanotechnology is overturning the existing dominant technology paradigm. Similarly, it is the authors' contention that nanoeducation will require overturning (or at least seriously rethinking) conventional educational paradigms.

The primary focus of the present work was at the post-secondary level. College and university research faculty tend to be at the cutting edge of emerging disciplines, and are therefore uniquely positioned to help define what students need to know to be successful in those fields (e.g. in NSE). Furthermore, colleges and universities are less constrained by the need to align teaching and learning with state or national education standards, and can therefore serve as catalysts and pace-setters for education reform. There is reason to believe, however, that the findings of this work should have broad and important ramifications for nano-education at all levels. In fact, the conver-

gence of 'big ideas' and learning goals between post-secondary and K-12 levels discovered in this work is an encouraging indication of a growing consensus regarding what students need to know to be successful in nanoscale science and engineering at all levels of STEM education.

The objectives of the present work were twofold. First, to help identify the core 'big ideas' of nanoscale science and engineering within the context of post-secondary education, and to cast them into a broad curricular framework—what we refer to as the 'P-N-P-A rubric' (Processing-Nanostructure-Properties-Applications). Second, to evaluate a representative sample of available NSE degree programs in the US for programmatic balance (against the big ideas of NSE and across the P-N-P-A continuum), including important aspects such as interdisciplinarity (a unique attribute of NSE), access to advanced NSE instrumentation and societal impact (ethics, safety, policy issues and so on). Recommendations were also made regarding the implementation of balanced degree programs in NSEE (NSE Education).

TOWARD A CONSENSUS OF 'BIG IDEAS' IN NSE

During 2006 and 2007, a series of national workshops was held to help define and to clarify a set of big ideas and learning goals in nanoscale science and engineering at the K-12 and/or 13–16 levels. A major study was also undertaken of learning outcomes that would be relevant to the post-secondary education landscape, and to correlate these outcomes with industry needs.

It is helpful to begin by defining what is meant by 'big ideas'. They are core concepts that are critical for basic competency in a given field (e.g. nanoscience) because these concepts are the building blocks for the development of a deep understanding of other concepts in that field [18]. These core concepts are often cross-disciplinary, i.e. they are big ideas in science rather than more narrowly conceived concepts in sub-fields such as chemistry or biology. A key question answered by a 'big idea' statement might be, 'What are the fundamental ideas students need to know to understand nanoscience/nanotechnology?'

In June, 2006, the National Science Foundation funded a national Nanoscience Learning Goals (NLG) Workshop dedicated to reaching consensus on big ideas in nanoscience for grade K-12 learners [18]. The NLG Workshop was sponsored jointly by the National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT) and SRI International, and was held at SRI in Menlo Park. Thirty-nine leading scientists and science educators participated in the workshop. They were chosen to represent the cross-section of disciplines involved in NSE and education—NSE researchers, NSE educators, learning scientists and science education experts. This expert

panel included both basic and applied scientists/engineers, with expertise in chemistry, physics, biology and materials science. The educators participating in the workshop brought expertise in the learning sciences and in both formal and informal science education contexts.

After brainstorming and reaching consensus concerning the big ideas in NSE, breakout groups worked to articulate and to clarify each big idea, including illustrative phenomena for that big idea that might be used in curriculum materials. Each group also began to identify links between their big idea and existing K-12 national standards and benchmarks. The findings of the NLG Workshop are captured in a document entitled, 'The Big Ideas in Nanoscale Science and Engineering' [18].

In August, 2006, an NCLT Faculty Workshop in NSE Education was held at California Polytechnic State University at San Luis Obispo. Thirty-two faculty representing 17 colleges/universities attended the workshop, of which a third were from community/technical colleges and the remainder from four-year colleges/universities. Virtually all attendees were already active in nanoscale research, nano-related education, or both. As with the NLG Workshop, there was a good balance of expertise—about one-quarter each from chemistry, physics, materials science/general engineering and the learning sciences. Although there was no representation from the biological sciences, biology was strongly represented in the discussions. Workshop breakout groups brainstormed big ideas in nanoscale science and engineering at the post-secondary level. It is important to note that the participants in the NCLT Faculty Workshop were kept unaware of the results generated during the NLG Workshop. Each participant was also responsible for developing learning goals and an action plan for incorporating nanoscience in his/her course or degree program. The resulting big ideas from what we will refer to as the NCLT Faculty (NCLT-F) Workshop were extracted from breakout group reports and the learning goals submitted by each faculty member, and are reported here for the first time.

The lists of big ideas derived from both the NLG and NCLT-F workshops are shown in Table 1. Detailed descriptions of each big idea are provided in Table 2, along with illustrative examples of nano-related phenomena. The order of big ideas on these lists is not meant to imply an overall learning trajectory. For example, mastering the 'tools' for the imaging and characterization of nanomaterials and nanostructures could very well be the starting point for a given NSE curriculum, as could mastering their fabrication, through 'self-assembly', for example. It should also be noted that certain topics came up as big ideas in one of the workshops, but not in the other. The NCLT-F participants, for example, felt that 'quantum mechanics' was an essential prerequisite for understanding 'tools' such as the scanning tunneling microscope and 'size-dependent properties' at the university level. What is important about these two lists—the NLG Workshop that focused on big ideas for the K-12 curriculum and the NCLT-F Workshop that examined big ideas for the undergraduate curriculum—is the strong overlap between these lists, as shown in Table 1.

The results generated by the two workshops (NLG and NCLT-F) were vetted by the larger nanoscience/nano-education community at several venues. The results were presented at the symposium on 'Learning at the Nanoscale' at the International Conference of the Learning Sciences at Indiana University in Bloomington, Indiana (July, 2006). The participants were generally supportive of the results and provided valuable feedback. The 'Big Ideas of Nanoscience' for grades K-12 and grades 13-16 were further reviewed at the NCLT center-wide meeting in November, 2006, and presented at a symposium held as part of the annual meeting of the National Association for Research in Science Teaching (NARST) in New Orleans in April, 2007. Particular attention was paid at these meetings to reconcile differences between the big ideas on the two lists in Table 1. There was considerable discussion and debate, for example, as to whether 'dominant forces' ('surface-dominated behavior' on the NCLT-F list) should be a big idea distinct from 'self-assembly'. At the post-secondary level, the faculty viewed these as

Table 1. 'Big Ideas' in NSE emerging from the Nanoscience Learning Goals Workshop and the NCLT Faculty NSEE Workshop [18]

Nanoscience Learning Goals Workshop (June, 2006, SRI International, Menlo Park) NLG Workshop 'Big Ideas'	NCLT Faculty NSEE Workshop (August, 2006, Cal Poly State Univ.-San Luis Obispo) NCLT-F Workshop 'Big Ideas'
Particulate Nature of Matter Size & Scale	Size & Scale Surface-to-Volume Ratio Surface-Dominated Behavior Self-Assembly
Dominant Forces Self-Assembly	Quantum Mechanics Tools & Instrumentation/Characterization Size-Dependent Properties Models & Simulations Societal Impact/Public Education
Tools Properties of Matter Modeling Technology & Society	

Table 2. Unpacking of 'big ideas' in nanoscale science and engineering

Big Idea	Description	Illustrative Examples
Size & Scale	<p>“At the nanoscale, factors relating to size and scale (e.g., size, scale, scaling, shape, proportionality, dimensionality) help describe matter and predict its behavior.” [18] Students must be able to appreciate and compare the sizes of objects on all scales, not just those that can be seen or seen with the aid of an optical microscope. In this big idea, “size” is defined as the actual extent, bulk, or amount of something. “Scale” has several dimensions, linking the size of an object to a numerical representation in conventionally defined units (e.g. meters, grams, etc.).</p>	<p>The dimensions of C-60 buckyballs (approximately 1 nm in diameter) or single-walled carbon nanotubes (also approximately 1 nm in diameter), are a billion times smaller than a 1-meter “Smart car,” a million times smaller than the thickness of a dime, or 10,000 times smaller than the diameter of a human red blood cell.</p>
Surface-to-Volume Ratio	<p>As the size of an object is reduced to the nanoscale (1-100 nm), the fraction of atoms at the surface increases dramatically. This is quantified by the ratio of surface area-to-volume or surface-to-volume ratio. The dramatic increase in the fraction of atoms at the surface of nanoparticles is partly responsible for their unusual surface-dominated behavior.</p>	<p>A cube 1 centimeter on a side is sliced into 10 slices in the x, y, and z directions. The surface area of the now 1000 smaller cubes has just increased from 6 cm², or the area of a large postage stamp, to 60 cm², the area of a typical credit card. If we continue subdividing down to cubes of 1 nm on a side, the surface area becomes 60,000,000 cm² or 6000 m², about 50% larger than the size of a football field in the U.S. and only slightly smaller than an Olympic soccer field.</p>
Surface-Dominated Behavior	<p>“All interactions can be described by multiple forces, but the relative impact of these forces changes with scale.” [18] On the nanoscale, a variety of electrical forces (e.g. van der Waals forces) with varying strengths tend to dominate the interactions between objects. As a result, inter-particle forces and energies play a much more important role than at the micro- or macro-scale.</p>	<p>The combination of high surface-to-volume ratio and prevailing van der Waals forces has explained the exceptional ability of geckos to climb vertical glass walls and points the way for developing advanced adhesives. Similarly, the depression of melting point in nanoparticles vis-à-vis their bulk counterparts can be explained as surface-dominated behavior. Chemical catalysis is yet another example of a surface-dominated behavior.</p>
Self-Assembly	<p>“Under specific conditions, some materials can spontaneously assemble into organized structures. Furthermore, this process provides a useful means for manipulating matter at the nanoscale.” [18] Self-assembly dominates in nature, e.g. the organization/assembly of biological tissues.</p>	<p>Under proper conditions (chemical, thermal) and in the presence of catalyst particles, carbon nanotubes self-assemble to impressive lengths. Guided assembly and alignment of carbon nanotubes is an essential step toward realization of mass-produced carbon nanotube-based electronics, i.e. “nanoelectronics.”</p>
Quantum Mechanics	<p>As the size/mass of an object approaches the nanoscale, classical mechanics must be replaced by quantum mechanics (emphasizing the dual particle-wave nature of matter) to adequately describe the interactions between objects and also their interaction with electromagnetic radiation, e.g. light. Students need quantum mechanics to understand the operation of fundamental nanoscale characterization tools and to understand size-dependent properties (electronic, magnetic, and optical).</p>	<p>The scanning tunneling microscope depends upon quantum mechanical tunneling for its operation. Below 10 nm, gold particles lose their metallic properties, e.g. they are no longer conductors. This can only be explained on the basis of quantum mechanics. Additionally, lasers (used in CD and DVD players) cannot be adequately understood without reference to quantum mechanics.</p>
Size-Dependent Properties	<p>The properties of matter can change with size and scale. In particular, as the size of a material approaches the nanoscale, it often exhibits unexpected properties that can lead to new functionalities [18]. Size-dependent properties can be either surface- or bulk-dominated. Surface-dominated properties result from the increased number of atoms on surfaces (see “Surface-Dominated Behavior” above). Bulk-dominated properties have to do with the reduced number of bulk atoms within nanoparticles.</p>	<p>Whereas macro- and micro- gold specimens are shiny, gold in color, and exhibit the typical metallic properties of malleability and conductivity, at the nanoscale the properties of gold become size-dependent. For example, color changes from the familiar yellow at the macroscale to various colors at the nanoscale (e.g. colloidal suspensions of gold spheres of ~100 nm diameter are red and transparent instead of gold and opaque). Color also changes with particle shape at the nanoscale. The size-dependency (and shape-dependency) of objects in the nanoscale accounts for the great scientific and technological interest in nanomaterials.</p>

Table 2 (cont.)

Big Idea	Description	Illustrative Examples
Tools & Instruments/ Characterization	Throughout history, the development of new tools and instruments has helped drive scientific and technological progress. “The recent development of specialized tools has led to new levels of understanding of matter, assisting scientists and engineers to detect, manipulate, isolate, measure, fabricate, and investigate nanoscale matter with unprecedented precision and accuracy.” [18] Students must be facile with such advanced instrumentation if they are to be successful in nanoscience/ nanotechnology careers.	The development of electron microscopes (both scanning and transmission) and the more recent “atom probes” (scanning tunneling microscopes, STMs, and atomic force microscopes, AFMs) allows scientists and engineers to both image and manipulate materials and structures on the nanoscale (1-100 nm) and even to the level of individual atoms.
Models & Simulations	Because nanoscale objects and phenomena are, by their very nature, too small to see, models and simulations are essential to aid in understanding, visualizing, and predicting their behavior. Models and simulations are also essential for the engineering design and fabrication of nanostructured materials and devices.	Models and simulations allow scientists to confirm and engineers to exploit the processing-nanostructure, nanostructure-properties, and properties-applications linkages of the P-N-P-A continuum, the former for the furtherance of nanoscience, the latter for the engineering of novel nano-structured materials and devices.
Societal Impact	As is true of all technological innovation, nanotechnology has great potential for impacting our lives in both positive and negative ways. Not only must practitioners (nanoscientists and nanotechnologists) be cognizant of these issues, but an educated citizenry will be called upon to make informed policy decisions regarding the future risks vs. benefits of nanotechnology to society.	Nanotechnology is poised to improve our quality of life, e.g. through advances in healthcare, improvements in water quality, and developments in sustainable energy. On the other hand, there is the potential for increased health risks. For example, nanoscale objects are small enough to pass through conventional water purification systems and are capable of penetrating the biological barriers that protect living organisms. There is increasing concern about health risks associated with the unchecked promulgation of nanoscale materials.

related, but separate, big ideas (NCLT-F). Hence, ‘self-assembly’ and ‘surface-dominated behavior’ were kept as distinct big ideas in the present work. On the other hand, the concept of ‘the particulate nature of matter’—that ‘all matter is composed of atoms that are in constant motion’ [18]—was deemed to be rudimentary for incoming freshmen to colleges and universities. This was viewed as an important big idea for grades K-12, but not for grades 13–16. Furthermore, although participants thought that ‘surface-to-volume ratio’ might be subsumed under one of the other big ideas—either ‘size and scale’ or ‘size-dependent properties of matter’—the faculty attending the NCLT-F Workshop recognized that virtually all introductory courses in NSE at the undergraduate level devote significant time to a treatment of surface-to-volume ratio. For the purposes of this paper, it therefore remained a separate big idea. Finally, ‘quantum mechanics’ was added as a big idea in nanoscience, but only for grades 13–16. The larger group indicated that students in grades K-12 could be made aware that there are ways of understanding the behavior of matter other than using classical mechanics, but they should not be expected—save for exceptional circumstances (honors, advanced placement classes)—to move beyond that level of understanding. At the undergraduate level, however, there was a strong consensus that ‘quantum mechanics’ is truly a big idea, critical for understanding everything from

‘tools’ to ‘size-dependent properties’ of nanomaterials and devices.

Another recent limited due-diligence study was conducted by SRI International, the Boeing Corporation, Foothill-De Anza Community College (FHDA), and the NCLT to examine learning outcomes at the college/university level, and to correlate them with industry needs identified by Boeing and prior analyses of industry [19]. One part of the study was an analysis of work performed at Boeing related to the design, engineering, fabrication and characterization of high performance aircraft materials. This was undertaken to identify the key competencies within each of the four areas (design, engineering, fabrication, characterization) and where, in a typical engineer’s training, these competencies were developed.

An extensive analysis was also made of courses and programs in materials science, polymer science and composites, materials characterization, and fabrication. Approximately 400 courses from a cross-section of four-year colleges and universities across the US and roughly 100 workshops were analyzed for course objectives, learning outcomes, and identified competencies. A similar analysis of courses on nanoscience/nanotechnology at the NCLT institutions (Northwestern University, University of Michigan, Purdue University, University of Illinois at Urbana-Champaign, and University of Illinois at Chicago) was also undertaken, involving 150 formal courses and 15 non-

credit short courses. The academic course/degree program analyses were evaluated in light of the competencies deemed relevant for the aerospace industry. Findings from the Boeing-SRI-FHDA-NCLT study are captured in the document, *Nanoscience: A Vehicle for a Goals-Oriented Science Education* [19].

Specific findings and recommendations of what we will refer to as the Boeing study will be discussed further below. However, it is illustrative to mention the four key nanotechnology competencies related to the aerospace industry highlighted in this report. They include:

- *Nanofabrication*: how nanomaterials and nanostructures can be fabricated.
- *Characterization and Modeling*: how nanomaterials and nanostructures can be imaged/characterized and the modeling of novel nanostructures for applications.
- *Surface Chemistry and Engineering Competencies*: a deep understanding of surfaces and the roles they play in engineering applications.
- *MEMS/NEMS, Sensors, Micro/Nano Devices (Smalltech)*: the key aerospace nano-applications considered by the Boeing study. (MEMS stands for ‘micro-electro-mechanical systems’. For NEMS, replace ‘micro’ with ‘nano’.)

These areas of competency map closely onto the P-N-P-A (processing-nanostructure-properties-applications) rubric.

A RUBRIC FOR POST-SECONDARY DEGREE PROGRAMS IN NANOSCIENCE AND NANOTECHNOLOGY

We have organized the big ideas in nanoscience/nanotechnology in Table 1 according to the rubric in Figure 1 with the goal of illustrating the essential curricular features and relationships for degree programs in NSE. The general design of this rubric is adapted from the field of materials science and engineering (MSE). Meyer [11] identified two subfields—instruments and materials—as overlaying the three major nanotech user industries: pharmaceuticals, chemicals, and electronics. Nobel laureate Richard Smalley states that, ‘Chemistry, physics, and materials science are at the core of nanotechnology’ [20]. The Boeing study concluded that, ‘The competency models for materials science as compared to nanotechnology suggests that mastery of the fundamental concepts within a materials science program prepares students to advance into nanotechnology’ [19]. Given the strong linkages between NSE and MSE at the postsecondary level it seems appropriate to borrow and adapt this educational framework from MSE to assist with the curricular development of the emerging discipline of nanoscience/nanotechnology.

But precisely what does the MSE discipline entail? As early as 1974, the COSMAT report [21] helped identify the central features of what

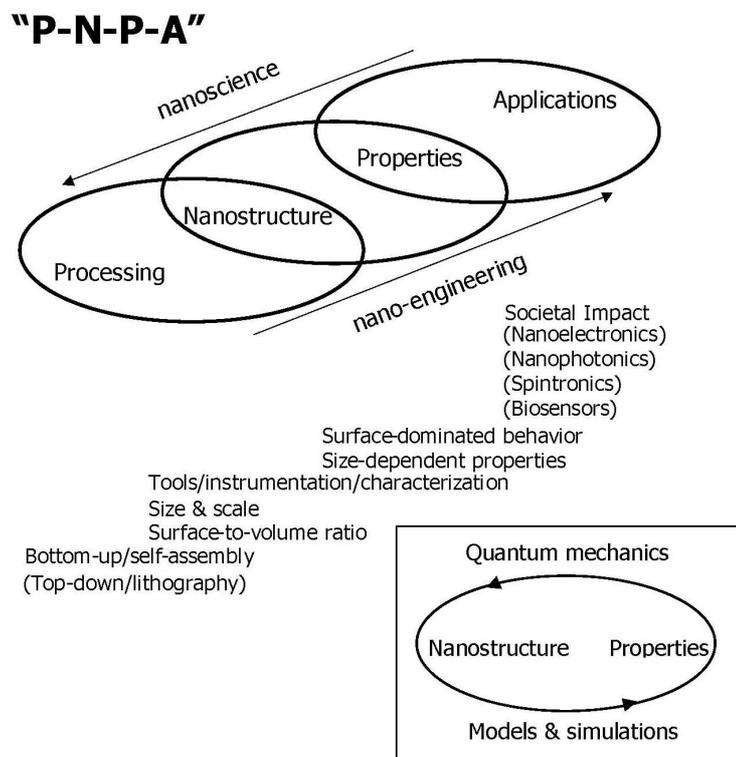


Fig. 1. The P-N-P-A rubric for degree programs in nanoscale science and engineering. The inset diagram shows cross-cutting big ideas that enable NSE at the chain-links of the main diagram.

was, at that time, the emerging discipline of MSE, namely structure (at the time primarily referring to 'microstructure'), properties, processing and performance [21]. These four key features have since become the main framework for education in MSE, with various diagrams being employed to link them together. The chain-link model, after which Figure 1 is designed, was developed at Northwestern University [22]. The initial link is between processing and structure (or nanostructure in Fig. 1), i.e. that there is a vital link between processing (how we make things) and their resulting structures (or nanostructures for NSE). The second link is between structure and resulting properties, i.e. that the structuring of nanomaterials or devices governs their ultimate behaviors and functions. Just as structure-property relationships lie at the heart of MSE, nanostructure-property relationships lie at the heart of NSE. The final link is between properties and performance, or as in Fig. 1 between properties and applications.

As mentioned previously, the four essential areas or nodes of the P-N-P-A rubric in Fig. 1 map well onto the four recommended 'nanotechnology competencies' identified in the Boeing report—nanofabrication, characterization/modeling, surface chemistry/engineering, and devices (NEMS, sensors, etc.) [19]. We have opted to use the term 'processing' as opposed to 'fabrication' to encompass both large-scale nanoparticle manufacturing (e.g. catalysts, sun-blocking agents) and fine-scale nanopatterning (e.g. nanolithography). The arrows above and below the four overlapping ellipses or chain-links in Figure 1 indicate the essential activities of nanoscientists and nano-engineers. The former—nanoscience—explores and explains the underlying nanostructure-property and processing-nanostructure relationships in nanomaterials and nanodevices. The latter—nano-engineering—on the other hand, exploits the processing-nanostructure and nanostructure-property relationships to design and fabricate novel devices for end-use applications.

The big ideas of NSE in Table 1 are organized in columns beneath the appropriate nodes of the P-N-P-A diagram. Self-assembly, for example, is listed beneath processing along with top-down methods such as photolithography. (Photolithography is set in parenthesis because it appears to be a tacit big idea, inasmuch as it is usually taught alongside bottom-up methods in most courses dealing with nanoprocessing.). It should be stressed that certain aspects of dominant forces (in the NLG Workshop [18]) are subsumed under the big idea of self-assembly. Several big ideas are listed under nanostructure, including tools/instrumentation/ characterization, size and scale and surface-to-volume ratio. The big ideas of surface-dominated behavior and size-dependent properties are appropriately listed under the properties node. Societal impact is listed under the applications node in keeping with the idea that nanotechnology is driven by the aim to advance broad societal

goals but that, as with other technological advances, nano-products may impact our lives in both positive and negative ways [18]. The other entries (in parentheses) under applications are not big ideas as such, but rather key applications domains mentioned by faculty attending the NCLT-F Workshop in their course and degree program learning goals. These are illustrative of representative nanotechnology applications impacting society.

Two additional big ideas in NSE—quantum mechanics and models and simulations—were identified as cross-cutting big ideas spanning the P-N-P-A continuum, i.e. they were deemed to be fundamental to understanding nanoscience/nanotechnology at all levels. Furthermore, they were understood to apply to the chain-links of Fig. 1 rather than the nodes. This distinction is captured in the inset diagram of Figure 1. For example, quantum mechanics is essential for understanding processing-nanostructure and nanostructure-property relationships (as shown in the inset diagram). Similarly, models and simulations are useful for making predictions across the P-N-P-A continuum, e.g. predicting nanostructure based upon processing, predicting properties based upon nanostructure, and predicting performance (applications) based upon properties. Models and simulations can be used for nanoscience (to explore/understand P-N-P-A relationships) and for nanotechnology (to exploit P-N-P-A relationships in the design of nano-based applications).

Before proceeding to the evaluation of degree programs, it must be stressed that the rubric of Figure 1 also attempts to capture the inherent interdisciplinarity of NSE. We view interdisciplinarity as having multiple dimensions, e.g. the science (discovery) vs. engineering (design) axis, and the disciplinary axis, e.g. physical/chemical vs. biological sciences. The importance of this theme was consistently highlighted at both the NLG Workshop [18] and the NCLT-F Workshop. Furthermore, the Boeing study [19] stressed that students need to be prepared to function in multidisciplinary environments, working on teams with experts from multiple disciplines, and dealing with issues across the P-N-P-A spectrum. Interdisciplinarity may not be unique to the field of NSE, but the extent to which it figures into the successful practice of NSE in industry may distinguish it as a non-negotiable ingredient of nano-education [19]. Although interdisciplinarity was not elevated to the status of a big idea at the NCLT-F Workshop, there was strong consensus that a balanced education in NSE (conforming to the P-N-P-A rubric) requires interdisciplinary exposure.

EVALUATION OF EXISTING NSE DEGREE PROGRAMS

The nano-education rubric in Fig. 1 is intended as an aid for both the construction and the

evaluation of degree programs in nanoscale science and engineering at the undergraduate level. Beginning with the first reported PhD program in nanotechnology [23], degree programs in NSE (science/engineering) and NSEE (science education) have continued to emerge. Their number can be expected to grow rapidly with time. A representative sampling of such programs (largely in the US) is found on the degree program section of the NCLT Resource Portal [24]. A subset of these degree programs was analyzed according to the P-N-P-A rubric of Fig. 1 and the incorporated big ideas of NSE from Table 1.

The NCLT Resource Portal serves as a repository of resources for learning and teaching in nanoscale science and engineering. It includes a section devoted to existing and/or emerging post-secondary degree programs in NSE(E) [24]. Participation in the repository is voluntary and must be approved by the home institution. Programs come to be listed on the Portal by invitation (through web searches, reputation, and so on) or by referral, with input solicited by NCLT personnel. At the time this study was undertaken, there were 18 NSE(E) programs listed on the Portal. Although this is by no means an exhaustive list, it was thought to be representative of existing/emerging programs—a snapshot of what was currently available.

Sixteen of the programs on the Portal were catalogued as nanoscale science, engineering and technology degree programs, the other two were catalogued as nanoscience education degree programs. Seven of the 18 programs were two-year associate degree programs, four described ‘minor’ or ‘area of concentration’ BS degree programs, three were cross-cutting ‘emphasis’ or ‘certificate’ programs at either the B.S. or Ph.D. level, and four were advanced degree (M.S. or Ph.D.) programs. A wide range of disciplines was represented, including the natural sciences, materials science, medicine and engineering. It must be stressed that the collection of NSE(E) programs on

the NCLT Portal is by no means exhaustive; additional programs are being posted on a regular basis.

A subset of these degree programs was analyzed for NSE programmatic balance in terms of the P-N-P-A rubric of Figure 1. In particular, we were looking for evidence of coursework at each node/feature of the P-N-P-A diagram, and the depth to which the big ideas at that node could be identified in course descriptions. Such information was gleaned from three sources:

- 1) the verbal description of the overall program given on their NCLT web-page;
- 2) the list of courses given on the same web-page;
- 3) additional information about the program and courses offered (including course descriptions) on the host institution’s web site (a link to which is provided on the NCLT web-page).

What we were looking for was wording attesting to course content aligned with the big ideas and nodes in the rubric of Figure 1. Although our analysis considered course descriptions, it did not extend to the level of individual course outlines. A program was rated as strong at a given P-N-P-A node if more than one big idea was represented at that node in course titles/descriptions. Otherwise, that node was rated weak (a single big idea represented) or absent (no indication of course coverage at that node).

In Table 3 we provide an anonymous listing and evaluation of undergraduate degree programs, for which two or more nodes could be identified—10 of the 18 programs. Some of the other programs were in the early stages of development, with few or no courses listed, for which a meaningful evaluation could not be made. The 10 programs evaluated were divided into two categories: university programs and two-year community college programs. The final column gives a summary rating based on the following criteria: ‘balanced’ (all four nodes present with strong ratings), ‘partially balanced’ (all four nodes present, at

Table 3. Evaluation of NSE degree programs posted on the NCLT NanoEd Resource Portal [24] in terms of the P-N-P-A rubric of Fig. 1

NSE Program Type	Processing	Nanostructure	Properties	Applications	Summary Rating
University A	Strong	Strong	Strong	Weak	Partially Balanced
University B	Strong	Strong	Strong	Strong	Balanced
University C	Weak	Weak	Strong	Weak	Imbalanced
University D	Weak	Weak	Strong	Strong	Imbalanced
University E	Weak	Strong	Absent	Weak	Imbalanced
University F	Strong	Strong	Strong	Strong	Balanced
University G	Weak	Strong	Strong	Strong	Partially Balanced
Community College A	Strong	Strong	Strong	Strong	Balanced
Community College B	Strong	Weak	Absent	Strong	Imbalanced
Community College C	Strong	Weak	Absent	Strong	Imbalanced

least three of which are strong), and 'imbalanced' (two or more weak nodes, or one or more nodes missing altogether).

A major finding of this study is that few existing NSE programs have programmatic balance of instruction across the P-N-P-A continuum—courses and/or course content spanning the processing, nanostructure, properties, and applications continuum. Only three out of the ten programs were deemed to be balanced, two of the university programs and one of the community college programs. Generally, we found that research universities tend to emphasize nanostructure-property relationships, with less attention to one end (i.e. processing) or the other end (i.e. applications) of the rubric in Figure 1. The sample of community/technical colleges was admittedly small, but the data seem to reflect an emphasis on fabrication methods and applications, with less attention to in-depth nanostructure-property relationships, perhaps because these institutions face the special challenge of securing student access to cutting-edge nanocharacterization facilities.

One factor contributing to the lack of programmatic balance is the fact that many four-year nanoscience or nanotech degree programs exist within traditional discipline boundaries, e.g. physics, chemistry, materials science, or a specific engineering field. The lack of balance across the P-N-P-A spectrum can be explained by noting that it is unlikely that a single academic department will have all the faculty expertise necessary to provide a comprehensive NSE curriculum. This problem is even more severe at community colleges, where a very limited number of faculty members are responsible for the nanoscience or nanotech education program.

Of course, program deficiencies can be addressed by requiring students to take electives in underrepresented areas or nodes on the P-N-P-A diagram, preferably from diverse disciplines. This is not always possible, however. First, appropriate courses may be unavailable on a given campus. Second, program course requirements can be so demanding that there is little room for additional coursework in NSE. This is especially severe in the engineering disciplines, owing to existing stringent ABET (formerly Accreditation Board for Engineering and Technology, now ABET, Inc.) course requirements. A good example has to do with biology. The faculty at the NCLT-F Workshop deemed biology to be an essential course of study for future nanoscientists/ nanotechnologists, owing to the diversity of emerging biology-related nanotech applications. Unfortunately, with noteworthy exceptions (e.g. bioengineering and biomedical engineering), few engineering programs are flexible enough to allow students to take the organic chemistry and biology courses required to be facile with bio-related NSE. Third, access to appropriate courses in other departments may be restricted. An illustration, cited in the Boeing

report [19], involved student access to courses in engineering design as part of a balanced NSE curriculum. Unfortunately, for students in the natural sciences, engineering design courses are largely off-limits, whether formally (closed registration) or practically (students lacking sufficient background/prerequisites).

A noteworthy exception to this trend is the Nanomaterials course offered by Professor Mark Hersam at Northwestern University. This course is tailored for broad accessibility (students are welcomed from a broad cross-section of disciplines, both engineering and the natural sciences, including biology), and group dynamics (group project/problem-solving and design by multidisciplinary teams of students) [25, 26]. During 2004–2006, Hersam's Nanomaterials course attracted students from eight distinct departments: Materials Science and Engineering, Biomedical Engineering, Chemical and Biological Engineering, Civil and Environmental Engineering, Electrical Engineering and Computer Science, Mechanical Engineering, Chemistry and Physics. A similar sophomore-level course in nanotechnology, co-taught from seven disciplines, was recently introduced at Loyola Marymount University [10]. This course is of interest owing to its biological applications focus. Another attempt to bring design to groups that cross traditional disciplinary boundaries was created at Purdue for students from chemistry and chemical engineering [27].

This raises the important issue of interdisciplinarity. As mentioned previously, interdisciplinarity was deemed to be an essential feature of NSE by both the NLG and NCLT-F Workshops and in the Boeing report [19]. Students need to be exposed to the interdisciplinary milieu of nanoscience/nanotechnology in order to be prepared to function effectively in multi-disciplinary industrial environments. Unfortunately, we found that few college/university degree programs currently offer a truly interdisciplinary experience for their students. There are encouraging exceptions, however. For example, the University of New South Wales offers an interdisciplinary BS in Nanotechnology [28], and the University of Toronto offers an interdisciplinary Nanoengineering BS degree [29], both of which span discipline/department boundaries. Similarly, Purdue University has developed a Ph.D. certificate program, whereby future educators coming from a range of disciplines (science, engineering, education) can earn their certificate in NSEE [24]. Another innovative program is the Ph.D. Program in Nanotechnology at the University of Washington [30], whereby graduate students from 10 departments can earn a second Ph.D. in nanotechnology through laboratory rotations and interdisciplinary coursework.

At the core of NSE is the nanostructure node, i.e. how scientists and technologists are able to image, characterize and manipulate nano-entities. The big idea that captures this aspect of NSE is 'tools/instrumentation/characterization' in Table 1

and in Figure 1. Graduates of NSE degree programs should be familiar with advanced instruments, such as the STM and AFM. Our analysis looked for evidence of required laboratory experience, either explicitly in the program overview or in individual course names/descriptions. Only six of the 18 NCLT NanoEd degree programs were deemed strong in the nanostructure area, as seen in Table 3 above.

Lab experiences are essential for virtually all of the big ideas in Figure 1, but especially for ‘tools/instrumentation/ characterization’. Furthermore, such experiences aid the successful transition from campus to the workplace. Access to cutting-edge instrumentation such as STMs and AFMs should be a universal component of any nano-degree program. Unfortunately, this requires substantial financial investment in equipment dedicated to teaching (laboratory exercises) rather than strictly for research purposes. It is encouraging to see community colleges partnering with research universities to provide such valuable experience. For example, the A.A.S. program at Dakota County Technical College partners with the University of Minnesota to gain student access to advanced nano-instrumentation [31]. Another noteworthy example is the Nanofabrication Manufacturing Technology course at Penn State University [32]. Students from branch and community colleges across the state register for this capstone semester course, with hands-on exposure to state-of-the-art equipment and fabrication methods in the clean room facilities on the main campus. Multi-user instrumental facilities, such as the Birck Nanotechnology Center at Purdue University [33], provide another approach to hands-on exposure to state-of-the-art equipment and clean-room fabrication methods.

In our analysis, we also looked for underrepresented big ideas. One such big idea, common to both the NLG [18] and NCLT-F Workshops and the Boeing study [19], is societal impact. This is the recognition of the impact, for good or ill, of nanoscience/ nanotechnology on society. Analysis of the courses and degree programs posted on the NCLT NanoEd Resource Portal [24] indicates that few courses are currently dedicated to the impact of nanotechnology on society, including discussions of ethics, public safety, public education and social policy. It is conceivable that such content is covered as a sub-topic in individual courses, which were not examined to the detail of their course outlines. However, the consensus at the NCLT-F Workshop was that this is a seriously underrepresented area in undergraduate NSE education. Noteworthy exceptions are the prototype nano-ethics courses, Nanotechnology, Biology, Ethics and Society, at Cal Poly State University-San Luis Obispo [34] and Ethics in Nanoscience & Nanotechnology at the University of Central Florida [35]. Related efforts to introduce ethics within the context of graduate training can be found in the nanotechnology module of the

LANGURE (Land Grant Research Ethics) project at North Carolina State University [36]. To be successful, future nanoscientists and nanoengineers will need to be cognizant of and conversant in technology and society issues affecting the practice of NSE. Alternatively, to help reinforce their importance, societal impact topics can be woven into courses throughout the NSE curriculum.

Fortunately, many of the abovementioned issues related to NSE education are beginning to receive the attention they deserve. An excellent example is the recent compendium edited by Sweeney and Seal entitled, *Nanoscale Science and Engineering Education* [37]. Several chapters of this book are dedicated to the challenges and approaches being taken to introduce nanoscale science and engineering at the undergraduate level.

CONCLUSIONS

We began our discussion of NSE degree programs by suggesting that, just as nanotechnology, as a disruptive technology, is overturning the existing dominant technology paradigm, nanoeducation will require overturning (or at least seriously rethinking) existing dominant education paradigms. Based upon the results of two workshops—the 2006 Nanoscience Learning Goals (NLG) Workshop [18] and the 2006 NCLT Faculty Workshop in Nanoscale Science and Engineering Education—plus the Boeing-SRI-FHDA-NCLT study of college/university learning outcomes vs. industry needs [19], we have developed a broad curricular framework or rubric of big ideas/essential features for degree programs in NSE. The resulting rubric adapts an educational framework from materials science and engineering as applied to nanoscience/engineering in a P-N-P-A chain-link diagram. The identified big ideas in NSE are clustered at nodes or essential areas for NSE education: processing (how nano-entities are fabricated), nanostructure (how nano-entities are structured and imaged), properties (the resulting size-dependent and surface-related properties of nanostructured materials/devices), and applications (how nanomaterials and nanodevices can be designed and engineered for the benefit of society). It is suggested that the P-N-P-A rubric be used as an aid in the construction and evaluation of degree programs in nanoscale science and engineering.

Based upon the P-N-P-A rubric (Fig. 1) and its incorporated big ideas in NSE (Tables 1 and 2), an analysis was made of a sample of existing NSE(E) degree programs in the US posted on the NCLT NanoEd Resource Portal [24] in terms of programmatic balance and essential features of the P-N-P-A model, including interdisciplinarity (a hallmark of NSE), nano-instrumentation, and societal impact. It appears that few programs exhibit balance across the P-N-P-A continuum. One factor contributing to programmatic balance is

Table 4. Recommended solutions for various nano-education issues identified in the present work

Nano-Education Issues	Recommended Solutions
Balance of Program Content	Requiring course content spanning the Processing-Nanostructure-Properties-Applications (P-N-P-A) Continuum
Interdisciplinary Exposure	Offering truly interdisciplinary courses and/or requiring elective courses outside the home department
Experience with Advanced Nano-Instrumentation	Requiring one or more hands-on laboratory courses involving state-of-the-art nano-instruments (electron microscopes, STM, AFM, etc.)
Exposure to Nano-Related Societal Issues	Incorporating societal aspects into required nano-courses or requiring stand-alone “Nano & Society” courses

the fact that NSE degree programs tend to be centered in single academic departments, which most likely lack the faculty expertise to provide a balanced P-N-P-A curriculum. Furthermore, student access to elective courses that would help satisfy P-N-P-A balance is usually limited, either by demanding course requirements (by the home department) or limited access to those courses (by the guest department, e.g. via closed registration or stringent prerequisites). Two underrepresented, but essential, areas of study for future nanoscientists/nano-engineers are biology and design.

An unfortunate by-product of NSE programs being offered by traditional disciplines is the lack of student exposure to the unique interdisciplinary milieu of nanoscience/nanotechnology. Few degree programs currently immerse their students in truly interdisciplinary classroom, laboratory, and project work, with adequate exposure to alternate disciplines and points of view.

An essential feature of NSE education is the big idea of tools/instrumentation/ characterization—i.e. that students should receive training in the use of advanced instrumentation for imaging, characterizing and manipulating nanomaterials and devices. The nanostructure of nanomaterials and devices is what distinguishes them from conventional materials and devices. Therefore, the nanostructure node is deemed especially important in NSE education. This is largely a resource issue, with a wide variability in student access to advanced instrumentation afforded by existing

degree programs. Creative partnering between community colleges and research universities is one way to address deficiencies in this area.

It is also important to recognize that one of the big ideas that appears to be underrepresented in NSE degree programs is societal impact, i.e. coursework having to do with nano-related public safety issues, ethics, social policy, etc. Given the potential impact of nanoscience/nanotechnology on society, for good and for ill, degree programs should provide students ample preparation for dealing with such issues in their careers.

Table 4 summarizes the overall recommendations emerging from the present work in four key areas—balance of program content, interdisciplinary exposure, experience with advanced nano-instrumentation, and exposure to nano-related societal issues. Current work is aimed at the design of nano-education programs that satisfy these recommendations.

This work focused almost entirely on NSE(E) degree programs in the US, with some mention of prototype programs in Canada and Australia. A similar analysis of emerging NSE(E) degree programs in other places of the world, especially in Europe and Asia, would be of considerable interest to the broader nano-education community.

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