THE FUTURE OF MATERIALS SCIENCE AND MATERIALS ENGINEERING EDUCATION

A report from the Workshop on Materials Science and Materials Engineering Education sponsored by the National Science Foundation September 18-19, 2008 in Arlington, VA

TABLE OF CONTENTS

SUMMARY

From a reading of the numerous reports detailing next generation technologies and engineering challenges, it becomes readily apparent that one of the primary limitations to the growth of many if not most future technologies is the availability of materials with appropriate properties and performance characteristics. For example, a majority of the fourteen grand challenges in engineering issued by the National Academy of Engineering—including accessible clean water, economical solar energy, capturing CO_2, and restoring and improving the urban infrastructure—require that materials and material systems with properties and performance superior to today's materials be developed.[1] Similarly, the Basic Research Needs reports for future energy technologies from the Office of Basic Energy Sciences at the Department of Energy[2] as well as the road maps for transportation and semiconductor[3] technologies highlight developing advanced materials as being one of the primary challenges that must be overcome to enable the envisioned advances. Here it is important to appreciate that the material properties and performance required to enable these advances cannot be met by evolutionary progress but rather require revolutionary progress in our ability to synthesize and process materials with unique properties that can be controlled and manipulated to satisfy specific applications. Success will require unprecedented advancement in our understanding of how structure and composition dictate properties and performance, in our ability to manipulate at the atomic level composition and structure to fashion desired properties, and to do so at an accelerated pace such that the time from a material being a laboratory curiosity to being utilized in an engineering application becomes just a few years. These are daunting challenges that the materials scientists and materials engineers of today are beginning to address and future ones will have to solve. These challenges imply a continuing need for materials scientists and materials engineers for the foreseeable future. However, despite this need and the fact that the discovery of new materials was responsible for enabling several of the technological achievements of the last century, the exciting and vibrant disciplines of materials science and materials engineering (MSME) remain relatively unknown compared to physics, chemistry, and electrical, mechanical, aerospace, and civil engineering. This lack of recognition remains an obstacle for the MSME communities that must be addressed if they are to provide sufficient personnel to meet the challenges ahead.

The workshop on the future of materials science and materials engineering education, held in Arlington, Virginia on September 18 and 19, 2008, was sponsored by the National Science Foundation (NSF) under grant NSF-DMR 0826749. It was funded by divisions in two directorates: the Division of Materials Research (DMR), the Division of Physics (PHY), and the Office of Multidisciplinary Activities (OMA) in the Mathematical and Physical Sciences (MPS) directorate and by the Division of Research on Learning in Formal and Informal Settings (DRL) and the Division of Undergraduate Education (DUE) in the Education and Human Resources (EHR) directorate. Representatives from industry, K-12 education, federal agencies, national laboratories, and professional societies met with materials faculty members to discuss the status and future of the materials field and their allied disciplines.

The workshop was designed to engage members of the materials community from the rel-

1 National Academy of Engineering, Grand Challenges in Engineering, http://www.engineeringchallenges.org/.
2 US Department of Energy, Basic Research Needs Workshop Reports, http://www.er.doe.gov/bes/reports/abstracts.html.
3 International Technology Roadmap for Semiconductors, http://www.itrs.net/.

evant disciplines to begin discussing the challenges for improving materials science and materials engineering education. These challenges include (1) increasing public awareness of the discipline and its critical role in solving societal technological challenges; (2) increasing student interest in science and engineering in general, and materials science and engineering in particular in kindergarten through 12th grades (K-12); and (3) defining a common core knowledge base for undergraduate and graduate education between and across the multiple materials science and materials engineering programs as well as options that exist in formal materials departments and in other engineering and science departments.

Unlike students who might learn about materials in a classroom, the general public remains largely unaware of materials science and engineering as a discipline and as a potential career option. Yet it is the general public that ultimately provides the financial support for materials research and that benefits from the technological advances it enables. Learning how to communicate about the discipline to the general public is challenging from many viewpoints including, but certainly not limited to, understanding how members of the general public learn about science and engineering, what they find engaging, and knowing and delivering a message at the cognitive level appropriate to the target audience. The workshop asked how to introduce materials science and engineering to the public by way of the media and informal educational initiatives as well as what should be incorporated in the message.

The students now in the K-12 educational system will be the MSME students and recent graduates in 2020, and they will be deciding how to best utilize our resources to meet the nation's needs and to ensure a continuing competitive advantage to drive our economic growth. They are growing up in a time when materials innovations have enabled a myriad of technologies and devices that have changed their lives. In the future, they will be responsible for finding solutions that address our growing need for sustainable, environmentally friendly, and affordable energy, water, and clean air, as well as all the goods required for a technology driven society and economy. Engineered materials will certainly play an important role in enabling these solutions, and the workshop participants considered it important to introduce materials science and engineering concepts into K-12 curricula to educate both the next generation of scientists and engineers as well as to make the next generation materials science literate. The workshop participants therefore considered how materials science and materials engineering can and should be introduced into an already time-constrained curriculum while still satisfying state and federal educational requirements.

At the undergraduate level, the emphasis is on teaching students the fundamental concepts of materials science and materials engineering; at the same time the curriculum should teach the "soft" skills necessary for them to become competitive in an international workforce and to be sufficiently agile to move into and lead emerging areas. The workshop asked what skills and tools prepare graduates to attend to multidisciplinary problems in a rapidly changing world. For the materials science and engineering designated departments, the foundation of the discipline is clear and is grounded on the synthesis/processing, structure/composition, property, and performance/application tetrahedron as applied to all classes of materials from metals, ceramics, polymers, and semiconductors to optical materials, biomaterials, and organic solids. The foundation is less well defined in materials programs, options, and minors that are appearing in other science and engineering departments. Here, for obvious reasons, the emphasis tends to remain centered on the major discipline but with a strong focus on materials. Although this growth is a strong indicator about the health of the materials discipline, it does emphasize the challenge of defining what should constitute the core body of knowledge expected for a materials scientist and materials engineer.

The challenges facing graduates with master and doctoral degrees are in many ways similar to those finishing baccalaureate programs. Again, the challenge is to define what constitutes a core knowledge base of materials and how this will be taught given the array of science and engineering departments involved in materials research and materials education today. In addition to mastering the core requirements, students have an increasing need to learn the skills for leading international collaborations, being entrepreneurial, and communicating in appropriate formats.

Clearly, a two-day workshop with a restricted and limited number of participants is an inadequate forum to answer all the challenges facing the materials science and materials engineering community. However, it is hoped that the issues raised in this report and its recommendations will serve as the foundation for a much needed, broader and extensive examination of the future of materials science and materials engineering education.

Organizing Committee

- Laura Bartolo, Kent State University
- Robert Hamers, University of Wisconsin-Madison
- Ian Robertson, University of Illinois at Urbana-Champaign
- Chandralekha Singh, University of Pittsburgh
- Rob Thorne, Cornell University
- Joe Whitehead, Jr., University of Southern Mississippi
- Larry Woolf, General Atomics
- Greta M. Zenner, University of Wisconsin-Madison
- Sue Martin Zernicke, University of Wisconsin-Madison

Online Reference

http://www.chem.wisc.edu/2008_nsf_workshop/

This report on the results of the Workshop on Materials Science and Materials Engineering Education was sponsored by the National Science Foundation under grant NSF-DMR 0826749 and jointly funded by the Division of Materials Research (DMR), Division of Physics (PHY), and the Office of Multidisciplinary Activities (OMA) in the Mathematical and Physical Sciences (MPS) directorate and by the Division of Research on Learning in Formal and Informal Settings (DRL) and the Division of Undergraduate Education (DUE) in the Education and Human Resources (EHR) directorate.

SUMMARY OF THE RECOMMENDATIONS

Public Education and Outreach Recommendations

1. Research needs to be conducted to determine the current state of public understanding of materials science and materials engineering and the public's current or potential interest in the fields. This should be done in conjunction with the development of guidelines about the level of knowledge the general public should have about materials science and materials engineering topics. These activities are essential to enable crafting of effective messages and devising optimal communication strategies.
2. Research needs to be conducted to determine how members of the general public learn about materials science and engineering and what information they find important and exciting. For example, are materials stories that demonstrate the impact materials have had and will continue to have on society the optimal vehicle for delivering the message? The findings of such studies need to be communicated to those engaged in developing material designed to appeal to the general public.
3. Rigorous education research must be conducted to assess the effectiveness and impact of educational outreach activities tied to current National Science Foundation-funded MSME programs. The research should also include a study of the broader impact and outreach requirements on the careers and professional choices of early and late-career faculty.
4. Mechanisms need to be developed for disseminating the findings of educational research efforts to scientists and engineers engaged in MSME education and research. This will ensure that the findings have a broader impact that ultimately will influence how these scientists and engineers engage the general public.

Kindergarten Through 12th Grade (K-12) Education Recommendations

1. Existing K-12 MSME curricula should be assessed to determine their effectiveness, barriers to adoption and use, and means to overcome those barriers. The MSME community should help develop new or modify existing materials science and materials engineering curricula or curriculum supplements for grades K-12 that fill gaps in existing curricula. They should be versatile so they can be widely used. The curricula must respond to state and national science and technology standards, correspond to best practices regarding how people learn, and address the demands for 21st century skills. They should demonstrate the interdisciplinary nature of materials science and materials engineering and their significant impact on society. Associated assessments should provide evidence for their effectiveness across diverse populations.
2. The MSME community needs to encourage science, technology, engineering, and mathematics (STEM) students interested in education to consider K-12 STEM teaching as a profession and to develop the additional skills and knowledge required to become excellent teachers. MSME faculty should consider teacher preparation as an important part of their responsibilities and should work with faculty in education to encourage STEM students to consider K-12 teaching careers in science and math.
3. The MSME community must provide training and professional development opportunities for K-12 teachers to improve their knowledge of materials concepts and applications that are relevant to their classrooms. Camps and programs for teachers should

be critically assessed, and those that have been demonstrated to be effective should be expanded and more aggressively promoted within the materials community. Both training and subsequent support should be encouraged to ensure that teachers can continue learning and sharing their knowledge with the students. Teachers from diverse backgrounds should be represented in these activities.

4. The degree to which K-12 students and teachers are aware of materials related careers and career paths should be determined. The MSME community should create MSME career descriptions using media that are most effective with students, make them available to schools, and assess their impact. Existing MSME education and teacher training programs should include information about MSME careers that teachers can share with students. Outreach tools should show students how careers in MSME play a critical role in modern society.

Undergraduate Education Recommendations

1. The broad-based materials community should seek funding for a National Academies study on the current status of and future needs for materials education in the USA. National concerns for ensuring security and continued economic growth, as well as sufficient energy and fresh water supplies in an efficient and sustainable manner should motivate the study. How to prepare materials students to address these concerns needs to be evaluated using a global context, recognizing the changing character of materials development, research, and manufacturing.
2. Curriculum revision should seek novel ways to include biology, business, project management, leadership, entrepreneurship, and international experiences into undergraduate education. Educators should explore a variety of implementation strategies. The University Materials Council,[4] the council of the heads and chairs of materials science and engineering departments and programs nationwide, should assess ongoing curriculum revision in departments across the country and disseminate best practices.
3. MSME educators should consider online educational programs to continue teaching traditional materials areas as faculty expertise in these areas is lost and these courses are displaced to accommodate ones in emerging areas. This medium might be especially beneficial at smaller schools and for granting continuing education credits.
4. To attract more students to the discipline, materials programs should change the message used to engage prospective undergraduates. The discipline is an enabling one and one that has the potential to provide technological solutions to critical societal issues. This type of message needs to be used to excite students about opportunities in the field.
5. Research, internship, and industrial experiences, both domestic and foreign, are important for the preparation of future materials scientists and engineers. Undergraduate students need research experiences even as early as the freshman year.

Graduate Education Recommendations

1. A benchmarking study of the current state of MSME graduate education should be undertaken with the goal of determining the breadth and depth within the various programs. The outcome of this study could serve as the foundation for the MSME community to define a common core body of knowledge. At a minimum it is recommended that all graduate programs in materials science and materials engineering define the mission and goals of their MSME degree program. The core principles should be inclusive of the relationships between (1) structure, (2) property, and (3) processing, and (4) application/performance of materials.
2. Materials science and materials engineering Master's programs should not be externally certified. This recommendation reflects the diversity of the student body pursuing MSME as well as the range of engineering and science departments offering such degrees.

4 For information on the University Materials Council see http://www.umatcon.org/.

3. Academic policies and procedures need to incorporate and sustain interdisciplinary research and training into materials science and materials engineering graduate programs. Interdisciplinary activities include inter-departmental and intra-departmental activities such as developing interdisciplinary courses, creating interdisciplinary degree programs, and creating interdisciplinary faculty appointments to meet the expanding academic and career needs of materials science and materials engineering graduates.
4. The MSME community should consider if the discipline-centric approach to graduate education is providing the best education and training for our students or if it is time for a different educational model, perhaps one that takes a more holistic approach, to be developed and implemented.

1. PUBLIC EDUCATION AND OUTREACH

1.1 Introduction

Educators who engage the public about materials science and materials engineering generally hope:

1. *to increase public knowledge of MSME,*
2. *to teach policy makers about materials and how MSME serves society, and*
3. *to encourage future scientists and engineers to pursue careers in materials-designated and -related fields.*

To attain these goals, those engaged in public education and outreach need to:

- *develop and deliver messages that are appropriate to target audiences and that are fitting to broad and diverse educational backgrounds.*
- *appreciate that members of the general public will experience different levels of excitement than educators and researchers do about particular topics. For example, members of the public are more likely to be interested in nanotechnology and its social, economic, and technological impacts than in the property changes that occur at the nanometer scale because of very high surface-to-volume ratio.*
- *understand how different segments of the public learn about technological advances and what delivery methods are most likely to appeal to target groups. For example, television series such as* Numb3rs *or forensic science programs have spurred increased interest in mathematics and forensic science, while science breakthroughs reported in the news media impact public knowledge and perception about that topic.*

During this session, members of the workshop discussed the issues outlined above and deliberated how to engage with people across the broad public spectrum and what messages about materials to share with them. The participants discussed how to use the media and informal educational programs to open forays for learning. They concluded that education researchers and experts in public communication, especially as related to science and engineering, need to disseminate their findings to the MSME communities such that public engagement and education becomes more effective. The foundation for the discussion and for the recommendations, which are given at the end of this section, was set by the presentations "The Science of Effective Communication: Lessons for Public Outreach" by Dietram Scheufele jointly from the Department of Life Sciences Communication at University of Wisconsin-Madison and the Center for Nanotechnology in Society at Arizona State University and "Connecting the Public with Materials Science—Sustainable Approaches" by Shenda Baker from the Department of Chemistry, Harvey Mudd College.

1.2 What does the public know?

Designing strategies to reach the different segments of the population and to achieve the desired goals begins with knowing what the public already understands about materials science and materials engineering.[5] Although there are no data specific to MSME, the National Science Foundation's *Science and Engineering Indicators 2008*[6] provides some data relevant to this question in terms of general science. For example, Table 1 illustrates the public's level of understanding of general science questions and how this has changed with time. What this study revealed was that the public's level of actual knowledge about science has on average not changed significantly over a ten-year period. There is also a generational effect with younger segments of the population fairing best. Furthermore, it can be concluded that the public's knowledge and understanding of science and engineering in the United States vary across the population and are impacted by factors such as gender, age, education, number of science and math courses taken, socioeconomic status, occupation, race, and ethnicity. Regarding MSME in particular there are no specific data, but based on anecdotal information, the workshop participants felt that the public in the United States knows very little about MSME and that many, if not most, might not be aware that MSME are separate and distinct disciplines from other science and engineering fields. This was disappointing to the workshop participants given the number of technological innovations that have been enabled through discovery and mass production of new materials with superior and often unique properties. At issue is how to educate the public about the crucial role materials science and materials engineering have played and will continue to play in enabling life-changing technological advances.

1.3 What Should the Public Know?

Having discussed what members of the general public know about materials science and engineering, it is important to consider the minimum amount of knowledge that members of the general public should have about materials science and materials engineering topics and for what purpose is it necessary for them to have that knowledge. The level of knowledge scientists and engineers believe members of the public should have is often at odds with what they actually know or are interested in learning. For example, in his book *Why Science?*,[7] Trefil, a physics professor and an expert in scientific literacy, argues that to engage in meaningful discussion about abortion and stem cell research, the general public must understand that:

> "As cells in the embryo divide, they become specialized and are no longer able to turn into any kind of adult cell,
>
> The most promising way to obtain stem cells is to harvest from an embryo, killing the embryo in the process,
>
> Up to eight cell divisions, cells do retain the ability to develop into any adult cell (totipotence) and hence are called stem cells."

and that is all. Whether this is right or wrong is an open question and is one that is certainly worthy of study and debate as it will shape how messages for the public are crafted.

Unfortunately, no one has conducted a similar exercise of identifying core concepts for materials science and materials engineering and the workshop discussion focused more on philosophical issues. One such issue involved whether the emphasis should be specifically on materials science and materials engineering or using materials science and materials engineering as the vehicle to convey a broader message about science and engineering. The participants were divided on this topic. The different goals of recruiting students to materials disciplines and cultivating a more science-informed citizenry, for example, might require different strategies. For educators supporting materials-specific public education, deploying a campaign to introduce the words "materials science," "materials (-related) research," and "materials engineering" into the public's vo-

5 Workshop attendees recognized and acknowledged that the public is not a single, homogeneous entity, but rather a group of people with a myriad of characteristics and backgrounds. This section refers to "the public" as a singular audience for simplicity.

6 National Science Board, *Science and Engineering Indicators 2008* (Arlington, VA: National Science Foundation, 2008), volume 1, NSB 08-01; volume 2, NSB 08-01A. Also available online at http://www.nsf.gov/statistics/seind08/start.htm.

7 James Trefil, *Why Science?* (New York: Teachers College Press, 2007).

TABLE 1. *Correct answers to scientific terms and concept questions, by three factual knowledge-of-science scales and respondent characteristic: 1995–2006[6] (Continued on next page)*

CHARACTERISTIC	1995 (N = 2,006)	1997 (N = 2,000)	1999 (N = 1,882)	2001 (N = 1,574)	2004 (N = 2,025)	2006 (N = 1,864)
KNOWLEDGE SCALE 1						
All adults	56	56	57	60	NA[a]	59
Sex						
Male	61	62	62	65	NA[a]	65
Female	51	50	53	55	NA[a]	55
Formal education						
<High school	41	41	42	43	NA[a]	40
High school graduate	55	56	57	58	NA[a]	57
Baccalaureate	63	70	73	76	NA[a]	70
Graduate/professional	73	76	78	78	NA[a]	78
Science/mathematics education[b]						
Low	47	47	48	50	NA[a]	51
Middle	62	59	64	65	NA[a]	64
High	76	77	77	79	NA[a]	77
Family income (quartile)						
Top	NA	NA	NA	NA	NA[a]	67
Second	NA	NA	NA	NA	NA[a]	64
Third	NA	NA	NA	NA	NA[a]	59
Bottom	NA	NA	NA	NA	NA[a]	52
Age (years)						
18–24	60	59	62	61	NA[a]	63
25–34	61	59	60	64	NA[a]	59
35–44	59	61	61	63	NA[a]	62
45–54	57	57	59	64	NA[a]	62
55–64	48	52	53	57	NA[a]	60
65+	45	43	44	48	NA[a]	49
Minor children at home						
Yes	59	57	57	61	NA[a]	59
No	54	55	57	59	NA[a]	60
KNOWLEDGE SCALE 2						
All adults	57	57	58	61	58	60
Sex						
Male	62	62	63	65	63	64
Female	52	52	54	56	54	56
Formal education						
<High school	42	42	44	44	40	41
High school graduate	56	56	58	59	55	58
Baccalaureate	64	71	73	76	68	70
Graduate/professional	73	77	78	79	75	77
Science/mathematics education[b]						
Low	48	48	49	51	48	52
Middle	62	59	64	66	63	64
High	76	78	77	79	74	77
Family income (quartile)						
Top	NA	NA	NA	NA	68	68
Second	NA	NA	NA	NA	61	64
Third	NA	NA	NA	NA	55	59
Bottom	NA	NA	NA	NA	49	53

TABLE 1 *Continued*

CHARACTERISTIC	1995 (N = 2,006)	1997 (N = 2,000)	1999 (N = 1,882)	2001 (N = 1,574)	2004 (N = 2,025)	2006 (N = 1,864)
Age (years)						
18–24	60	58	62	62	63	62
25–34	61	60	61	64	61	59
35–44	59	62	62	64	62	62
45–54	59	58	60	64	60	63
55–64	50	54	55	58	57	61
65+	47	44	47	50	47	50
Minor children at home						
Yes	59	58	58	62	60	59
No	55	56	58	60	56	60
KNOWLEDGE SCALE 3						
All adults	53	53	56	58	56	NA[c]
Sex						
Male	58	59	60	63	61	NA[c]
Female	49	49	51	54	52	NA[c]
Formal education						
<High school	39	39	41	41	37	NA[c]
High school graduate	52	53	55	56	53	NA[c]
Baccalaureate	61	69	71	74	66	NA[c]
Graduate/professional	71	74	77	77	73	NA[c]
Science/mathematics education[b]						
Low	45	45	46	48	46	NA[c]
Middle	59	56	61	64	61	NA[c]
High	74	76	76	78	72	NA[c]
Family income (quartile)						
Top	NA	NA	NA	NA	66	NA[c]
Second	NA	NA	NA	NA	59	NA[c]
Third	NA	NA	NA	NA	52	NA[c]
Bottom	NA	NA	NA	NA	46	NA[c]
Age (years)						
18–24	57	56	59	60	62	NA[c]
25–34	58	57	59	62	60	NA[c]
35–44	56	58	59	61	60	NA[c]
45–54	56	55	57	62	57	NA[c]
55–64	46	50	52	55	54	NA[c]
65+	43	41	43	47	44	NA[c]
Minor children at home						
Yes	56	55	56	60	58	NA[c]
No	52	53	55	57	54	NA[c]

NA = not available

[a] Not all questions for knowledge scale 1 asked in 2004.

[b] Low = ≤5 high school and college science/math courses; middle = 6–8 courses; high = ≥9 courses.

[c] Not all questions for knowledge scale 3 asked in 2006.

NOTES: Table includes all years for which data collected. Factual knowledge of science scales 1, 2, and 3 include responses to:

- The center of the Earth is very hot. (True)
- All radioactivity is man-made. (False)
- It is the father's gene that decides whether the baby is a boy or a girl. (True)
- Lasers work by focusing sound waves. (False)
- Electrons are smaller than atoms. (True)
- Antibiotics kill viruses as well as bacteria. (False)
- The universe began with a huge explosion. (True)
- The continents on which we live have been moving their location for millions of years and will continue to move in the future. (True)
- Human beings, as we know them today, developed from earlier species of animals. (True)
- Does the Earth go around the Sun, or does the Sun go around the Earth? (Earth around Sun)

Knowledge scale 1 also includes responses to: How long does it take for the Earth to go around the sun? (One year); asked only if respondent answered correctly that Earth goes around Sun. Knowledge scale 3 also includes responses to a question on meaning of DNA. Knowledge scale 2 does not include either of these two questions.

SOURCES: National Science Foundation, Division of Science Resources Statistics, Survey of Public Attitudes Toward and Understanding of Science and Technology (1995–2001); University of Michigan, Survey of Consumer Attitudes (2004); and University of Chicago, National Opinion Research Center, General Social Survey (2006). Science and Engineering Indicators 2008 cabulary might increase awareness of the fields. Educators who supported the goal of improved general scientific literacy viewed MSME examples as potential tools for teaching fundamental science concepts. It was recognized that a MSME-centric educational effort could also serve as a vehicle for improving general scientific literacy and that focusing education initiatives on materials-specific concepts could simultaneously promote MSME as a distinct and important discipline. This is a topic worthy of debate as both options have merit.

Participants also debated the efficacy of educating the public on scientific content and/or the scientific process. Some participants argued that teaching the scientific process is a challenging yet valuable component of public education efforts. If people understood and could apply the scientific process, they could make more informed science-related decisions in their lives. Grasp of the scientific process was viewed as especially important for risk assessment, research funding, and voting processes. Of course, educators teaching the scientific process must introduce it at an appropriate level so that learners will be able to understand and use it. Other participants held the view that members of the general public would not be interested in learning the scientific process, especially as an introduction to MSME. Interesting facts about how materials have affected and will continue to impact society, the job market, national security, economic growth, and national competitiveness might be of greater interest to the public. Educators teaching materials concepts to the public need to learn how these broader issues can be employed to teach core concepts about materials and their properties. Here again a quantitative assessment of what the public should know and why they should know it is needed so that appropriate strategies can be developed and implemented.

1.4 How Does the Public Learn About Materials Science and Materials Engineering?

How the general public learns about scientific and engineering information is another issue that needs to be answered before devising an effective strategy to improve and enhance its knowledge. Newspapers, magazines, books, television, radio, the Internet, and movies are examples of vehicles for delivering messages to the general public. Even advertising on billboards and bus shelters can capture the public's interest, provided the message is of the appropriate form.[8] Materials scientists and materials engineers need to comprehend how people, especially different generations, obtain their information and which media to use to reach the target audience and to increase impact and effectiveness of the outreach effort. There is a significant body of scholarly research that identifies important elements of media communication as well as public communication of science,[9] but it is largely unknown within the MSME community—this is a situation that should be remedied if this community is to use its time and resources effectively in engaging with the public.

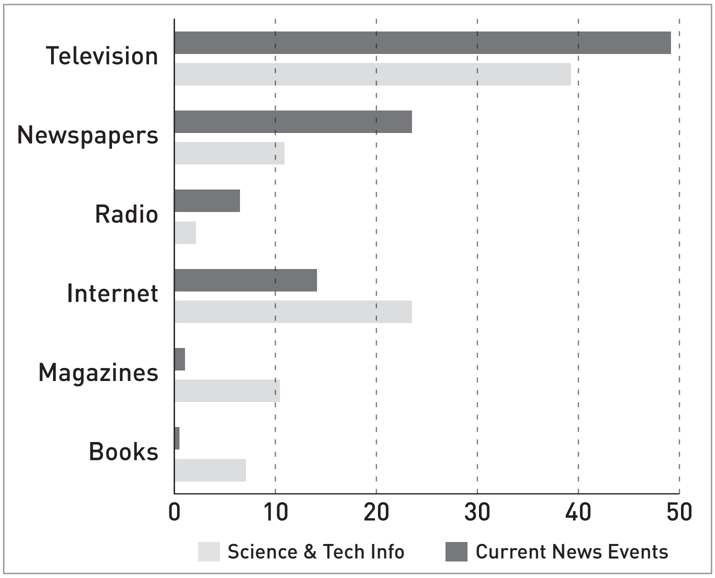

FIGURE 1. *The percentage of the US public using each type of media as its primary source to learn about current news events and science and technology*[10]

Insight to how the general public obtains information about science and technology is available. For example, the 2006 results of the General Social Survey conducted by the University of Chicago National Opinion Research Center and further presented in the NSF *Science and Engineering*

8 Stuart Naylor and Brenda Keogh, "Science on the Underground." *Public Understanding of Science* 8 (2):105-122.
9 See, for example, *Journal of Communication*, *Communication Research*, *Science Communication*, *Mass Communication and Society*, *Public Understanding of Science*, *Journal of Research in Science Teaching*, *Science Education*, *International Journal of Public Opinion Research*, and *Public Opinion Quarterly*.

Indicators 2008 report showed that the primary source for learning about science, engineering, and current events was through television, although the Internet, magazines, and books were important for science and technology information but less so for current news (see Figure 1).[10] Given the importance of television as a delivery vehicle, the workshop participants considered what is available now and what is needed. Videos for communicating science and engineering and documentaries tracing the impact of materials on society already exist; see for example, *Connections*, a ten-episode documentary television series created and narrated by science historian James Burke. In addition, the American Institute of Physics, along with the National Science Foundation and Ivanhoe Broadcast Network, Inc., produces the *Discoveries and Breakthroughs Inside Science (DBIS)* video series,[11] and ASM International Education Foundation[12] conveys information through the Internet by producing and posting podcasts. The production of short video-based stories could be a simple way to communicate the value and importance of materials science and materials engineering; see, for example, the website Science TV.[13] If this approach is chosen, the videos should be cataloged in a central repository so that they can be readily accessed and used by educators. However, before embarking on major video productions, its effectiveness at reaching the targeted segments of the population needs to be determined.

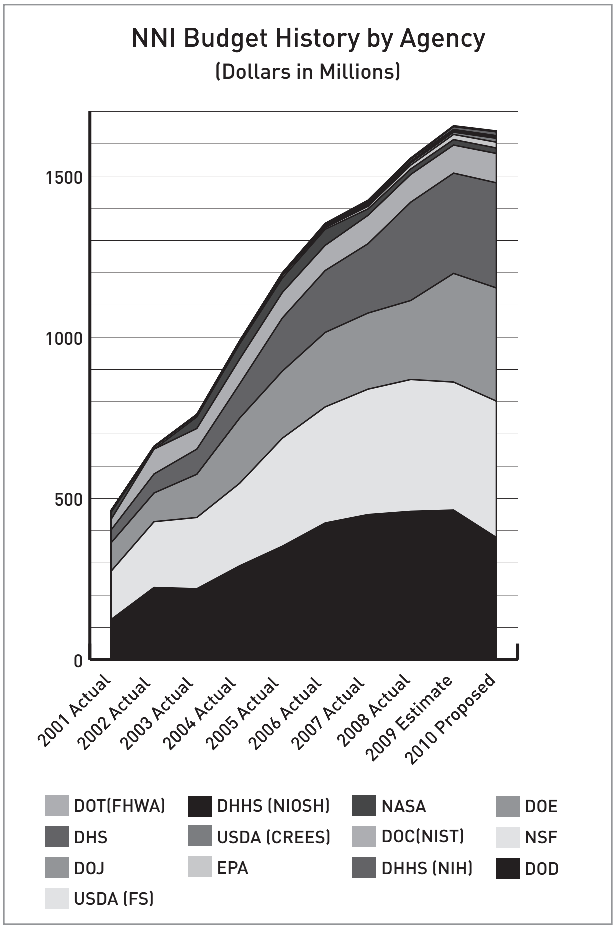

FIGURE 2. *Expenditures in nanotechnology by federal agency for the period from 2001 to 2008*[19]

The General Social Survey also found that for information about specific scientific topics the primary source of information was the Internet.[10] Given this information, the participants considered what MSME specific web sites were available. One notable site for engaging the public is the Strange Matter site.[14] They also found that some of the information content that is available, such as on Wikipedia, needs attention—this should be a relatively easy one for the community to address. A central website with general materials information and needs could be another way to disseminate information through popular channels.

An equally important point to consider is what message should be conveyed and how to design it so it is effective. The 2008 National Academy of Engineering report *Changing the Conversation: Messages for Improving Public Understanding of Engineering*[15] demonstrates that the message conveyed impacts the image of the engineering profession and its ability to excite, recruit and retain future engineers. They also showed that the image conveyed by the message is gender specific and that one message may appeal to males but not to females and vice versa. Although this study focused on engineering, the conclusions reached are probably

10 University of Chicago National Opinion Research Center, General Social Survey (2006), http://www.norc.org/projects/general+social+survey.htm, presented in National Science Board, "Chapter 7—Science and Technology: Public Attitudes and Understanding" in *Science and Engineering Indicators 2008*, vol. 1 (Arlington, VA: National Science Foundation, 2008), NSB08-01, http://www.nsf.gov/statistics/seind08/c7/c7s1.htm.

11 American Institute of Physics, *Discoveries and Breakthroughs Inside Science (DBIS)*, http://www.aip.org/dbis/.

12 ASM International, Education Foundation, http://asmcommunity.asminternational.org/portal/site/www/Foundation/.

13 Science TV, http://www.science.tv/.

14 Strange Matter, http://www.strangematterexhibit.com/. Other examples are the Chemistry and Materials page of the Science Museum website, http://www.sciencemuseum.org.uk/visitmuseum/subjects/chemistry_and_materials.aspx; The Virtual Physical Laboratory, http://resource.npl.co.uk/docs/educate_explore/vplab/vplab_overview.pdf; and The City of Materials website from ASM, International, http://www.cityofmaterials.com/portal/site/cityofmaterials/.

15 National Academy of Engineering. *Changing the Conversation: Messages for Improving Public Understanding of Engineering* (Washington, DC: National Academies Press, 2008), http://www.nap.edu/catalog.php?record_id=12187.

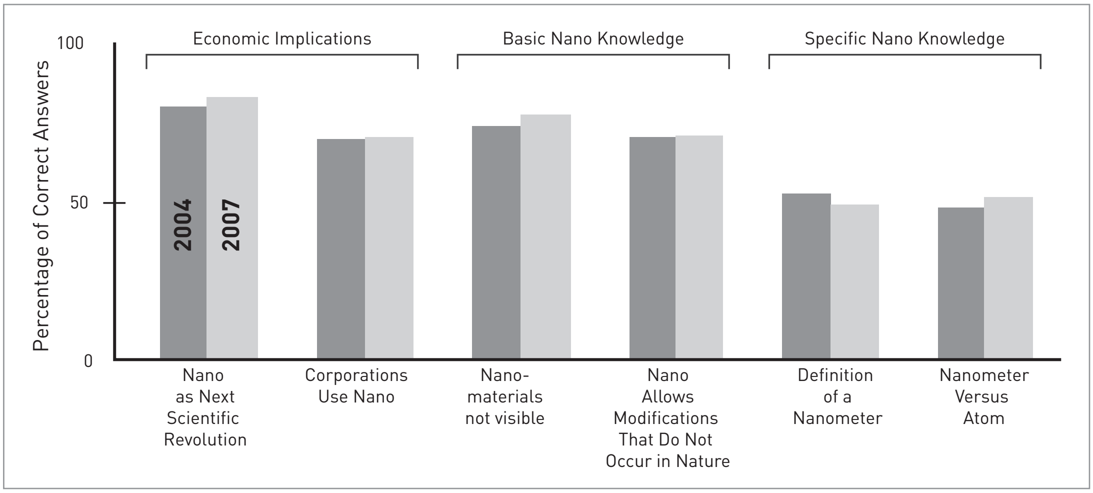

FIGURE 3. *Comparison of the percentage of correct answers by the public to nanotechnology questions in 2004 and 2007*[20]

equally applicable to many science disciplines. Scientists, engineers, and all public communicators must be knowledgeable about and aware of what public audiences already know, need to know and care about knowing if they are to craft effective and influential messages. The message must be appropriate for the targeted group. It was concluded that for materials scientists and materials engineers to meaningfully engage in educating the public, they should understand the importance of the message and should establish collaborations with journalists, marketers, graphic artists, video producers, web designers, educators, psychologists, business people, and other experts in communicating with the public.

One cadre of science communicators regularly educates the public with messages in the form of stories.[16] Professional science journalists and science writers hook readers by connecting science with human pursuits such as exploration, teaching, or healing. For example, the National Aeronautics and Space Administration explains the significance of space science and space exploration using their mission statement, which, in part, is: "To advance and communicate scientific knowledge and understanding of the earth, the solar system, and the universe."[17] Medicine is rich with stories about people caring for and healing those in need. Materials science and materials engineering needs to build and expand on describing how their work impacts people and society. Such articles, for example, could adopt the style of those in Beyond Discovery: The Path from Research to Human Benefit.[18]

Materials researchers need to become engaged in creating and communicating narratives about their fields to ensure that information is accurate and that the content is a balance between materials concepts, scientific process, and societal impact. The researchers' involvement highlights their concern for society and how they think critically about the interaction of their research with the broader world, improving, perhaps, the public's perceived image about scientists and engineers—that many are fun, exciting and engaging individuals.

Dietram Scheufele presented an interesting case study on the change in the general public's understanding of nanotechnology from 2004 to 2007. During this period, the total investment in nanotechnology through the National Nanotechnology Initiative alone increased from $1000M to about $1500M (Figure 2, on previous page).[19] Over the same time period there was an exponential growth in media coverage and from 2006 to 2008 the number of products featuring

16 Ivan Amato, *Stuff: The Materials the World is Made Of* (New York: Harper Perennial, 1998); Jeffrey L. Meikle, *American Plastic: A Cultural History* (Piscataway, NJ: Rutgers University Press, 1997); Stephen Fenichell, *Plastic: The Making of a Synthetic Century* (New York: Harper Business, 1997); Michael Riordan and Lillian Hoddeson, *Crystal Fire: The Birth of the Information Age* (New York: WW Norton & Co., 1997).

17 The Mission Statement and Vision of the National Aeronautics and Space Administration are available at http://naccenter .arc .nasa . gov/ NASAMission .html.

18 Beyond Discovery, http://www.beyonddiscovery.org/.

19 National Nanotechnology Initiative, http://www.nano.gov/html/about/funding.html.

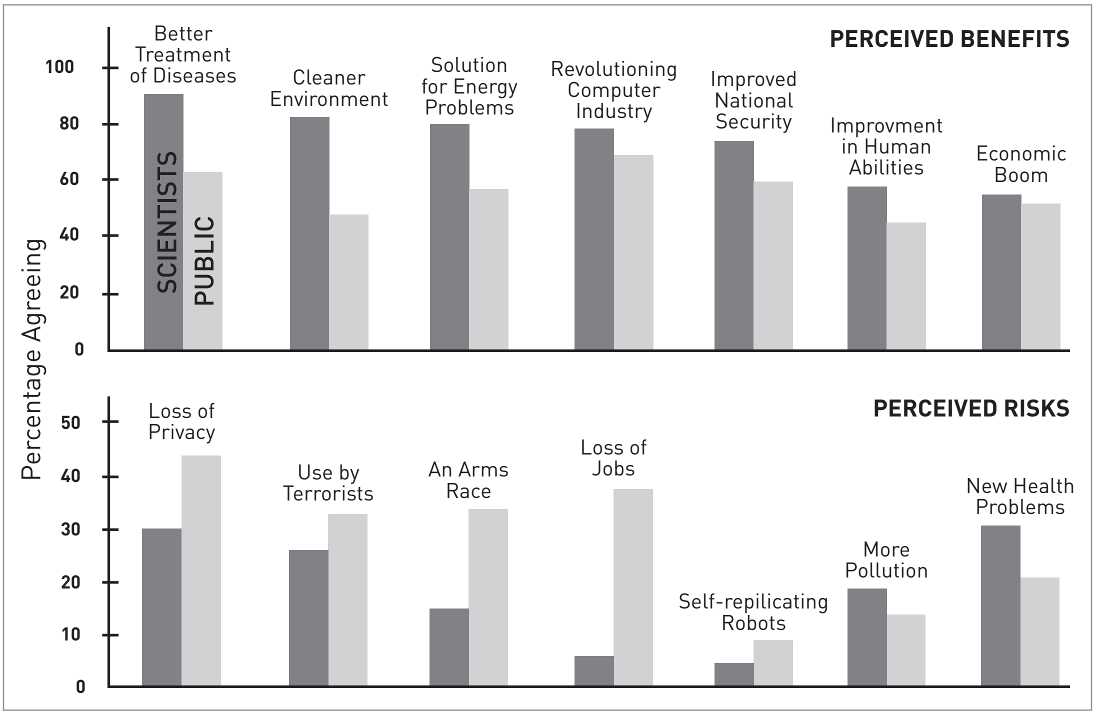

FIGURE 4. *Comparison of the perceived benefits and risks of nanotechnology between scientists and the public.*[20]

nanotechnology increased from 212 to 606. Given this level of expenditure, the associated increase in media coverage, and the number of new products, it is interesting to explore how the public's understanding of key nanotechnology concepts changed. Figure 3[20] (on the previous page) shows how the percentage of correct answers to questions relating to nanotechnology and its impact on the economy changed from 2004 to 2007. In each category, there has been little change, with no improvement about specific nanotechnology concepts such as how small a nanometer really is. Scheufele demonstrated that scientists are more optimistic than the general public about the benefits of nanotechnology and are less concerned about the perceived risks, see Figure 4.[20] From Scheufele et al.[20] it appears that the most important science and engineering aspects for the general public are more related to social and economic impact rather than the technological details that scientists and engineers find exciting.

1.5 How Can the Materials Community Promote Learning Using Informal Science Education?

Using the media to educate and reach out is one method to draw the public to materials science and materials engineering. Informal education—learning that is self-directed, highly personalized, and life-long[21]—can also be a powerful mode for engaging public audiences. It can spark the interest of future scientists and engineers.

Museums are ready venues for informal education. Shenda Baker described the successful materials exhibit Strange Matter that has toured the country since 2004. It targets middle school students but also appeals to families. Over two million people have visited the exhibit since its inception. While this number is impressive, neither a cost-benefit analysis nor a study on the effectiveness at reaching beyond the expected demographic group has been conducted. Clearly, quantitative assessment of the success and impact of such ventures is needed to help guide future initiatives.

Insight as to the effectiveness of using informal science institutes as a vehicle for communicat-

20 Dietram A. Scheufele, Elizabeth A. Corley, Sharon Dunwoody, Tsung-Jen Shih, Elliott Hillback and David H. Guston. 2007. *Nature Nanotechnology* 2: 732—734.
21 J. H. Falk, L. D. Dierking, and S. Foutz, *In Principle, In Practice: Museums and Learning Institutions* (Lanham, MD: Altamira Press, 2007). For the NSF's description of informal science education, see the Informal Science Education (ISE) program solicitation NSF 09-553, http://www.nsf.gov/pubs/2009/nsf09553/nsf09553.htm.

ing the message was given in the presentation by Scheufele. The data, shown in Figure 5, indicates that a minority of the American public visited a science or technology museum in the past year.[22] Since museum visitors are usually people with higher socioeconomic status, hosting events only at museums serves to maintain or even widen the gap between those who are well represented in MSME professions and those who are underrepresented. Museum-located projects, however, should not be abandoned; instead, efforts need to be broadened to include, for example, libraries, which serve a very large percentage of the public, or zoos and aquaria.

Workshop participants brainstormed about other informal venues that could host exhibits, demonstrations, programs, or performances about materials. They suggested community-gathering sites such as town festivals and community centers; religious institutions including churches, synagogues, and mosques; and hospitals. Other possibilities were places of commerce (e.g. supermarkets, shopping malls, and department stores such as Wal-Mart), casual restaurants (e.g. cafes, coffee shops, and fast food restaurants), and transportation arenas (e.g. airport, bus, and train terminals as well as buses, trains, and subways, and state Department of Motor Vehicles waiting rooms). In addition, efforts that support science and engineering activities in general, and explorations related to MSME in particular, that can be done inexpensively and safely at home should be encouraged, developed and promoted.[23]

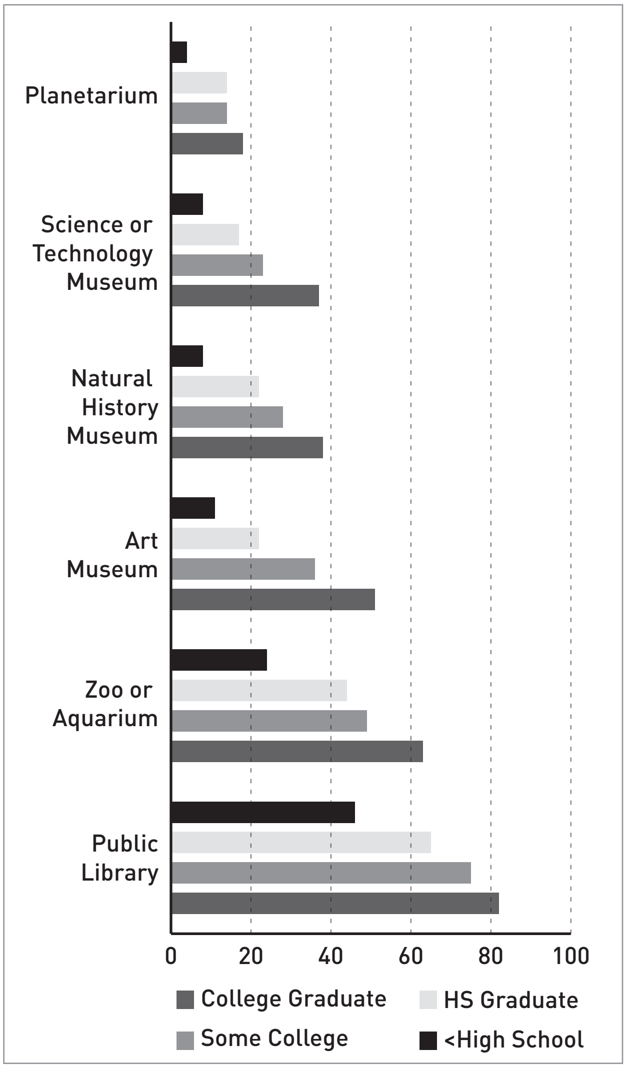

FIGURE 5. *Percentage of the public attending informal science institutions, by institution type and education level for 2006.*[22]

Whatever form informal education efforts take, they would be enhanced by coordination and collaboration between professionals inside and outside the fields of MSME such as museum educators, librarians, and education researchers. Having materials scientists and engineers working with academic researchers in education, marketing, or art, although beneficial, is not sufficient. Establishing collaborations with practicing professionals are central to producing, distributing, and marketing high-quality, effective educational materials and programs. Such collaborative efforts will help enhance learning, cultivate interest, and prevent MSME information from being misrepresented and misconstrued. Here it is important to stress that this effort reaches beyond academia and must involve the professional societies, both inside and outside the discipline, to maximize impact.

1.6 What is the Impact of Outreach Activities on the Career Development of Faculty?

The National Science Foundation effectively requires outreach as a component of research activities since according to NSF merit review criteria, investigators must explicitly address the broader impacts of their research. A successful proposal by a young investigator for a National Science Foundation Faculty Early Career Development Award is expected to include

22 National Science Board, *Science and Engineering Indicators 2008* (Arlington, VA: National Science Foundation, 2008), 1: 7-14, http://www.nsf.gov/statistics/seind08/start.htm. Of college graduates, less that 40% had attended a science/technology museum in the past year. For those with some college, approximately 22%; high-school graduates, 18%; and those who did not graduate from high school, less than 10%.

23 For examples, see the Try Science website, http://www.tryscience.org.

INCOMPLETE LIST OF POTENTIAL PARTNERS

- National Science Teachers Association (NSTA)
- National Association of Research in Science Teaching (NARST)
- Association of Science-Technology Centers (ASTC)
- Visitors Studies Association (VSA)
- Association of Children's Museums (ACM)
- National Library Association (NLA)
- American Association of Museums (AAM)

a significant effort in educational and outreach activities. The expectation is meant to ensure that early career researchers think seriously about the importance of science education and outreach activities; therefore, many NSF investigators in MSME-related areas have developed diverse tools and materials and communicated to the public about MSME. While the intent of this activity is commendable, little research related to the effectiveness of these outreach activities exists, and no systematic research has been carried out to evaluate the impact of these activities on the professional development of the researchers. The workshops participants recommend that such a study be commissioned.

1.7 Recommendations

The deliberations of the participants, which are summarized in the previous sections, led to the following recommendations:

- Research needs to be conducted to determine the current state of public understanding of materials science and materials engineering and the public's current or potential interest in the fields. This should be done in conjunction with the development of guidelines about the level of knowledge the general public should have about materials science and materials engineering topics. These activities are essential to enable crafting of effective messages and devising optimal communication strategies.
- Research needs to be conducted to determine how members of the general public learn about materials science and engineering and what information they find important and exciting. For example, are materials stories that demonstrate the impact materials have had and will continue to have on society the optimal vehicle for delivering the message? The findings of such studies need to be communicated to those engaged in developing material designed to appeal to the general public.
- Rigorous education research must be conducted to assess the effectiveness and impact of educational outreach activities tied to current National Science Foundation-funded MSME programs. The research should also include a study of the broader impact and outreach requirements on the careers and professional choices of early and late-career faculty.
- Mechanisms for disseminating the findings of the educational research studies to scientists and engineers engaged in MSME education and research need to be developed. This will ensure the findings have a broader impact that ultimately will influence how these scientists and engineers engage and communicate with the general public.

2. KINDERGARTEN THROUGH 12TH GRADE (K-12) EDUCATION

2.1 Introduction

The Glenn Commission's Before It's Too Late, *the National Academies'* Rising Above the Gathering Storm, *and many other reports call for improved science, technology, engineering, and mathematics (STEM) education at the K-12 level.*[24,25] *They concluded that national competitiveness and general scientific literacy are impetuses for renewed attention to the education of young people. But the primary and secondary educational system is complex, influenced by rules and regulations that are determined in part by each school, school district, state, as well as national entities.*[26] *While the improvement of all STEM education at the K-12 level is critical, workshop participants sought to define the appropriate role for materials science and materials engineering education at this stage and how to maximize its effectiveness and adoption in schools. This session considered four major areas: materials education standards, materials education curricula, professional development of teachers for materials education, and increasing student knowledge and interest in materials majors and careers.*

To set the stage for discussion, invited speakers Philip Sadler, Director of the Science Education Department of the Harvard-Smithsonian Center for Astrophysics, and Robert Chang, Professor of Materials Science and Engineering at Northwestern University, presented the state of STEM education in the United States and the characteristics of effective curricula. Each then described exemplary instructional materials at the middle and high school levels. They showed that assessments validate the materials' effectiveness and that the materials have a positive effect on diverse student populations. The main points of these talks provide the background and justification for the recommendations in this section.

Philip Sadler discussed reasons for pre-college engineering education. These include increased knowledge of engineering-specific concepts, improved inquiry skills, better understanding of how science and engineering solve human problems, and increased awareness of STEM careers. He emphasized that any K-12 science education curriculum should be grounded in evidence for its effectiveness and should attend to underrepresented groups. His data (Figure 6[27] *found on the next page) indicate that taking a science course in high school improves the grades of students taking that same science course in college. However, no cross-disciplinary effect was seen since, for example, taking high school physics did not improve the college chemistry grade. The largest improvement in college science grades, however, occurred when students had four years of strong math preparation in high school, indicating that students should take substantial mathematics and sciences courses in high school to be prepared for STEM majors in college. In addition, improvement in college science grades occurred when students took high school science courses that*

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24 National Commission on the Teaching of Mathematics and Science Teaching for the 21st Century, *Before It's Too Late: A Report to the Nation from The National Commission on the Teaching of Mathematics and Science Teaching for the 21st century* (2000), http://www.ed.gov/inits/Math/glenn/report.pdf.

25 National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (Washington, DC: National Academies Press, 2007), http://books.nap.edu/catalog.php?record_id=11463.

26 See, for example, "Science Education Through the Eyes of a Physicist" by Ted Schultz on the website Resources for Involving Scientists in Education, http://www.nas.edu/rise/backg2.htm.

27 Philip M. Sadler and Robert H. Tai "The Two High-School Pillars Supporting College Science." *Science* 317 (5837): 457—458, DOI: 10 .1126/science .1144214 .

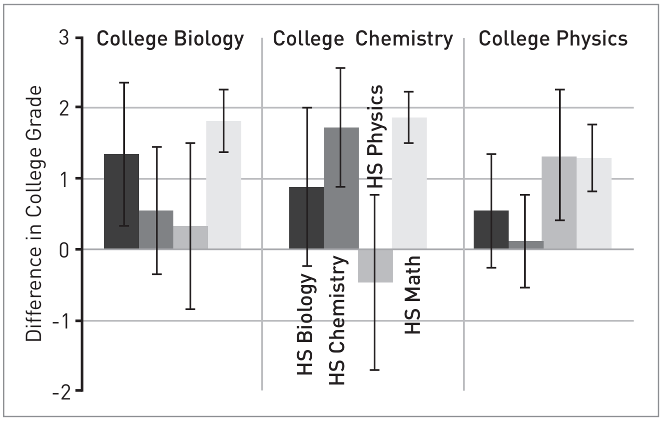

FIGURE 6. *College grades in science courses were most improved by taking four years of mathematics in high school and by taking the same science course in high school.[27]*

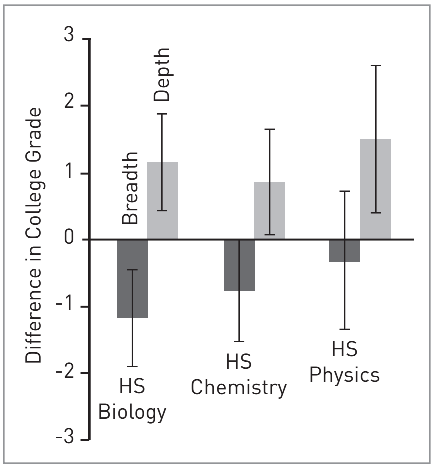

FIGURE 7. *College science grades improved for high school courses that emphasized depth over breadth.[28]*

focused on deep exploration of a few topics as opposed to a wide breadth of coverage (Figure 7[28]). These findings have implications not only for instruction at the K-12 level but at the undergraduate and graduate levels as well.

Sadler pointed out that successful middle school curricula that use design challenges to improve conceptual understanding of STEM concepts involve clear goals, tests against nature, multiple iterations, and large dynamic range. These characteristics are likely to be useful for engineering curricula that teach design, including materials-related curricula at the K-12 level and in higher education. (Further information on this study and the conclusions drawn from it can be found in Sadler and Tai.[27])

Robert Chang's talk reinforced and complemented Sadler's points. Chang emphasized the need to improve the education of high school graduates to prepare them to succeed in college or in the workforce. He noted that teachers tend to be isolated within departments and teach their subjects in a compartmentalized fashion, but curricula must include a strong emphasis on developing 21st century skills[29] that include solving open ended, complex, multidisciplinary problems with real world contexts.

The Materials World Modules (MWM)[30] are examples of inquiry and design based learning in materials-related curricula for middle and high-school students that were developed to meet the 21st century challenges (Figure 8). Chang explained that each module requires approximately two weeks to complete and that over 40,000 students have used a module. In a typical module experience, students interactively engage in an inquiry learning cycle and then a design learning cycle (Figure 9). These cycles are integral elements in curriculum design and are processes supported by extensive scientific literature.[31] MWM meet many of the state and national science standards, which are mandated by most school districts, and fulfilling them is critical for widespread use of any science curricula. Assessments indicate that boys and girls understanding increased by at least 2.5 standard deviations above the mean, with 0.8 increase considered significant, after completing a module.

2.2 Materials Education Standards and Curricula for K-12 Students

Sadler and Chang described the skills that students need for the future, the elements of successful elementary and secondary educational experiences, and the approach used by one set of successful materials science and materials engineering curricula. Given these insights, workshop participants discussed how to design appropriate curricula and to broaden adoption of materials-related topics in K-12 classrooms. Some suggested that widespread adoption would require a change in standards and policy, but change at the state and federal levels and, ultimately, the inclusion of MSME on high stakes tests seems unlikely. Existing K-12 standards fortunately appear to be adequate, as material concepts appear as cross-cutting

28 M. Schwartz, P.M. Sadler, G. Sonnert, and R.H. Tai, (in press) "Depth Versus Breadth: How Content Coverage in High School Science Relates to Later Success in College Science Coursework." *Science Education*, 93(4).
29 Partnership for 21st Century Skills, http://www.21stcenturyskills.org/.
30 Materials World Modules, http://www.materialsworldmodules.org/.
31 National Research Council, *How People Learn: Brain, Mind, Experience, and School* (Washington, DC: National Academies Press, 1999), http://www.nap.edu/openbook.php?record_id=6160, and Jo Handelsman, Diane Ebert-May, Robert Beichner, et al. 2004. "Scientific Teaching." Science 304: 521-523.

themes in many of the National Science Education Standards[32] including the following topics (grade strands appear in parentheses): Properties of Objects and Materials (K-4); Properties of Earth Materials (K-4); Abilities to Distinguish Between Natural Objects and Objects Made by Humans (K-4); Properties and Changes of Properties in Matter (5-8); Structure of the Earth System (5-8); Structure and Function in Living Systems (5-8); Structure and Properties of Matter (9-12); Chemical Reactions (9-12); Matter, Energy, and Organization in Living Systems (9-12); Geochemical Cycles (9-12); Abilities of Technological Design (9-12); Understandings About Science and Technology (9-12).

The materials community in conjunction with teachers and professional educators has already developed excellent middle and high school curricula, including the MWM and other K-12 materials modules by the National Science Foundation-funded Materials Research Science and Engineering Centers.[33] Other sources for materials-related curricula include The Institute for Chemical Education at the University of Wisconsin[34], science catalogs, national laboratory, university, and industry outreach programs, and commercial curricula. A question not addressed at the workshop but worthy of follow-up is whether comprehensive collections of materials-related curricula exist and are easily found, preferably on the web, and in a format ready for teachers to use.

Although materials-related instructional curricula have been developed and made available, they have not been widely adopted in middle and high schools; for example, according to Chang only 40,000 students have been exposed to the Materials World Modules. There are many possible reasons for this limited success. One obstacle could be the complexity of each local K-12 system, which includes state standards and local control of the curriculum. The trials of meeting high stakes testing requirements and the challenges of providing professional development activities to teachers might inhibit widespread use of these new curricula. The length of some modules might deter others from adopting them. MWM are time-intensive activities requiring one to two weeks for each module, which might not be the best match to the demands of all classrooms. The cost of curriculum materials is a barrier for many teachers. The workshop participants suggested further reasons for their limited adoption, and these issues could form the basis for future study.

Workshop participants discussed how to incorporate materials science and engineering topics into existing curricula with the aim of increasing awareness about materials and for designing new curricula. One approach would be for materials science and materials engineering educa-

Materials World Modules

- Composites
- Concrete
- Sports Materials
- Environmental Catalysis
- Introduction to the Nanoscale
- Manipulation of Light in the Nanoworld
- Biodegradable Materials
- Biosensors
- Food Packaging Materials
- Nanotechnology Module
- Ceramics
- Polymers
- Smart Sensors

FIGURE 8. *The topics of the Materials World Modules span many types and applications of materials.*

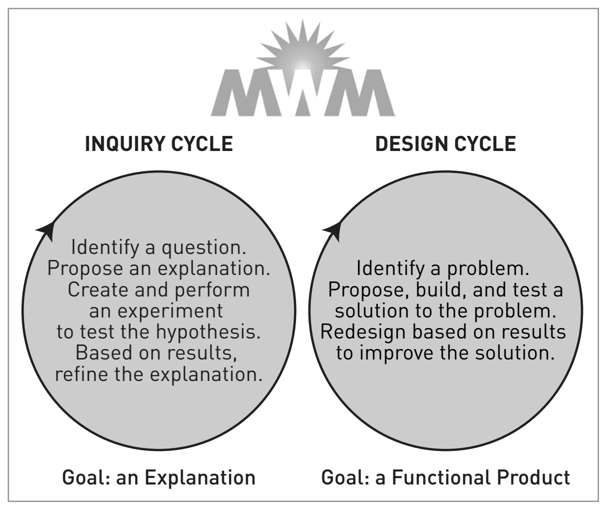

FIGURE 9. *Materials World Modules start with hands-on inquiry based activities that simulate the work of scientists and then conclude with a design challenge that simulates the work of engineers.*

32 Every state has its own science standards. Most, but not all, are based on the publication *National Science Education Standards*, developed by the National Research Council, http://www.nap.edu/openbook.php?record_id=4962. Project 2061 by the American Association for the Advancement of Science also delineates national science standards in the report *Benchmarks for Science Literacy*, http://www.project2061.org/publications/bsl/online/index.php.

33 K-12 materials education programs are available at http://mrsec.org/education/category/list_by_type/k-12/.

34 The Institute for Chemical Education, http://ice.chem.wisc.edu/.

tors to collaborate with textbook publishers to develop and include materials-related applications and problems. This is not an untried approach. For example, SCI-Links, a partnership between textbook publishers and the National Science Teachers Association, has been used for this type of curriculum enrichment.[35] Another approach would be for materials scientists and materials engineers to either develop short teaching modules that link core classroom concepts to applications of materials or materials-related careers or to map topics in existing or new materials modules to science standards; see, for example, NanoSense Activities[36] and the MWM Concept Modules. There are examples in other disciplines for how this can be done and we should learn from their experience. For example, the National Institutes of Health Curriculum Supplement Series and the National Academy of Sciences Beyond Discovery series could serve as models for modules and supplements.[37] Wider adoption of materials-related curricula will likely require attention to the local constraints as well as the generation of appropriate guides for teachers, including technical background information and content-specific pedagogy.

Materials have had a profound impact in society as evidenced by the naming of specific historical ages after them; one just has to consider the magnitude of the impact the development of engineering materials such as concrete, steel, and plastics has had on the growth of modern civilization. The importance of materials is unlikely to change since advanced materials with unique and superior properties will be central to enabling solutions to the grand challenges facing the nation and the world of tomorrow. The role materials have played in shaping society could be potential topics in courses such as history or economics. Educating students in the arts, humanities, and social sciences is seen as equally important as educating all science and engineering students about materials science and materials engineering.

Materials concepts can be taught at all grade levels if the information is at the appropriate cognitive level. Qualitative behaviors of different materials can be introduced in the early grades, with more complex materials properties and quantitative measurements coming later. For example, the Lawrence Hall of Science Full Option Science System kindergarten module on wood and paper[38] incorporates material science topics in its curricula without an explicit mention of materials science. At the other end of the K-12 spectrum, the introductory college curriculum *Teaching General Chemistry: A Materials Science Companion*[39] demonstrates that materials science can be a framework for teaching the chemical principles in traditional chemistry courses. This approach could be extended to high school science classrooms; the Materials World Modules have been a major step in that direction.

An extension of this approach could be the development of a comprehensive 1, 2, or 3-year high school science program that uses the inherent multidisciplinary framework of materials science and materials engineering to unite the disciplines of physics, chemistry, biology, and geology. Such an approach would be a high risk/high reward method to provide the requisite 21st century skills and perhaps would catalyze the removal of disciplinary barriers between high school science subjects as well as between high school science teachers. Indeed, a key aspect of incorporating materials science in K-12 may be as a means to explore the interdisciplinary nature of science and technology.

Some members of the workshop suggested exploring new models of collaboration to generate curricula. Instead of large institutional and medium-to-long term curriculum development efforts, a more local and short-term approach that draws on diffuse collective creativity and feedback might yield better outcomes. For example, a "crowd-sourced" Wikipedia-like environment, moderated by a combination of experts and registered users, could be more efficient. If so, NSF or others could fund the generation of a rolling list of topics and content challenges for the broader community and reward the development of highly rated and widely used content

35 SCI-Links enhances existing classroom materials by providing websites, news stories, activities, and discussion with experts, http://www.scilinks.org/tour/default.asp.

36 NanoSense Activities, http://nanosense.org/activities.html.

37 Curriculum Supplement Series, http://science.education.nih.gov/customers.nsf/WebPages/CSHome, and Beyond Discovery series, http://www.beyonddiscovery.org/.

38 Lawrence Hall of Science Full Option Science System, http://www.lhs.berkeley.edu/education/programs/foss.

39 Arthur B. Ellis, Margret J. Geselbracht, Brian J. Johnson, George C. Lisensky and William R. Robinson. *Teaching General Chemistry: A Materials Science Companion* (Washington, D.C.: American Chemical Society, 1993).

with substantial prizes. These activities could be hosted by or integrated within digital archives such as the National Science Digital Library, comPADRE, or the Materials Digital Library.[40]

A question raised by some of the workshop participants was the rationale for emphasizing materials-related topics to K-12 students, stating that it could be argued that many other topics were just as relevant and capable of providing a context for multidisciplinary science. The general sense of the materials scientists was that materials science has the unique characteristics of being an inherently multidisciplinary and integrative approach—one that unites core academic subjects, interdisciplinary themes, and technology with inquiry and design challenges, real world contexts, and open ended complex problems that perhaps could uniquely provide the basis for a model 21st century curriculum.

2.3 Professional Development of K-12 Teachers

While materials-related curricula are crucial for introducing materials concepts into classrooms, teachers are the integral link between the MSME community and K-12 students. Increasing the number of qualified K-12 teachers and training them to educate students about materials science and materials engineering will make the next generation of students aware of the discipline. Two highly qualified pools of candidates for becoming high school teachers are undergraduate and graduate students pursuing STEM degrees. However, this is a career path that is rarely mentioned as an option especially at the major research universities. To change this situation and support interested students, advisors, mentors and faculty need to emphasize the attributes of teaching—such as making a difference—that contribute to career satisfaction. The Physics Teacher Education Coalition (PhysTEC) and UTeach programs[41] might be useful models for increasing the number of highly qualified K-12 STEM teachers by fostering collaborations between science faculty, education faculty, and K-12 school districts.

K-12 teachers not trained in a STEM discipline often have little understanding of how their subjects connect with materials science and materials engineering. Consequently, there is little or no systematic discussion of materials in classes taught by this cadre of teachers. Teachers, however, are highly motivated to learn about and adopt classroom materials that help them attract and maintain the attention of their students. Educating these teachers about materials science and materials engineering, and science and engineering in general, is another avenue that should be undertaken. Materials science and engineering camps are one vehicle to educate teachers and to help teachers integrate MSME topics into their classrooms. At the ASM Teachers Camps[42], for example, teachers use materials curricula and are given both the classroom materials and the professional development needed to teach their own classes. Ensuring that teachers get continuing education credit further encourages motivated teachers to participate in the camps and programs; financial support for hosting these camps is also needed.

Providing teachers with follow-up support is also critical to fully integrate the lessons and activities into their routine and to ensure that the curricula do not "stay on the shelf." NSF's Graduate Teaching Fellows in K-12 Education Program[43] provides a model mechanism. For example, MSME advanced undergraduate or graduate students from local colleges or universities could partner with local schools to teach MSME topics under the guidance of a classroom teacher or to serve as a resource for teachers who have participated in a teachers' camp organized by the department. In the first scenario, the MSME student provides content training to a teacher, while the middle or high school teacher mentors the student for a potential career in teaching. Another NSF program that could be playing a much more important role in recruiting STEM undergraduates into STEM teaching is the Robert Noyce Scholarship program.[44]

As the MSME community develops and promotes materials training and curricula for K-12 teachers, results from educational research, as discussed by both Sadler and Chang, must

40 National Science Digital Library, http://www.nsdl.org; comPADRE, http://www.compadre.org; Materials Digital Library, http://matdl.org/repository/index.php.

41 Physics Teacher Education Coalition, http://www.phystec.org/about/index.php; UTeach , http://uteach.utexas.edu/.

42 ASM Teachers Camps, http://asmcommunity.asminternational.org/portal/site/www/Foundation/Educators/TeachersCamp/.

43 Graduate Teaching Fellows in K-12 Education Program, http://www.nsfgk12.org/.

44 Robert Noyce Scholarships, http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5733.

guide the initiatives. For students to acquire more accurate scientific understanding, teachers must know their students' preconceptions[45] and use proven strategies, such as the inquiry learning cycle[46], and relevant pedagogical content knowledge[47] to guide how they teach.

2.4 Career Awareness for K-12 Students

Participants in the workshop discussed the future materials workforce. They felt many students do not know that MSME is a field of study in college or a possible career choice. Most K-12 students are unaware of the terms "materials science" and "materials engineering." To improve MSME career awareness, existing education modules, such as Materials World Modules and those from the NSF-funded Materials Research Science & Engineering Centers, could include expanded information on MSME careers. Career web sites do exist[48], but their effectiveness is difficult to determine. Teachers should receive career information during training events, and middle school and high school career discussions should include various career pathways and real life examples.

To reach more students and to increase awareness further, the MSME community needs to disseminate career information through the media that is used by and appeals to the intended audience. For example, information can be posted on the Web (e.g. on popular career planning websites), in textbook sidebars, on posters, or in YouTube videos (see, for example, the recent YouTube video from the Department of Materials Science and Engineering at Pennsylvania State University[49]). Designing posters, possibly in conjunction with other engineering societies, and distributing them to high schools might be an effective strategy to inform students and teachers about MSME and other engineering careers. A key aspect in conveying the message is that the right one, the one that appeals to the students, is used. Portraying materials science careers as avenues to solving energy, environment, and sustainability problems might capitalize on the current generation of students' natural interest in these topics and their passion for making an impact. The need to change how we portray the discipline and our profession is clearly stated in the National Academy of Engineering report *Changing the Conversation: Messages for Improving Public Understanding of Engineering*.[50]

Another way to introduce students to materials is through popular culture. Television is a potential way to inform and excite students about MSME careers. Shows such as *ER* and *CSI: Crime Scene Investigation* are popular with students, with *CSI* generating a huge increase in student interest in forensics. Following the model of *CSI* or *Numb3rs*, many participants were interested in determining how to initiate a comparable MSME based show. Using the Science and Entertainment Exchange already developed by the National Academy of Sciences may be the most efficient method.[51] Another approach would be to work with existing science programs such as *NOVA* on Public Broadcasting Service channels or those on the Discovery Channel, History Channel, National Geographic Channel, or other science and technology channels. MSME topics and storylines suitable for these media should be identified and elaborated. Students are strongly connected to popular culture, which might be the best mechanism for reaching them. The workshop participants generally agreed that arousing mass student interest in MSME could require a collaborative effort between professionals from sociology, psychology, mass media, marketing, and economics.

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45 Useful resources include the Private Universe Project in Science, a video workshop for K-12 educators about teaching science, http://www.learner.org/resources/series29.html, and the Misconceptions-Oriented Standards-Based Assessment Resources for Teachers, http://www.cfa.harvard.edu/smgphp/mosart/index.html.

46 National Research Council, *How People Learn: Brain, Mind, Experience, and School* (Washington, DC: National Academies Press, 1999): 139. http://www.nap.edu/openbook.php?record_id=9853&page=139; Rodger W. Bybee, Joseph A. Taylor, April Gardner, Pamela Van Scotter, Janet Carlson, Anne Westbrook, and Nancy Landes, *The BSCS Instructional Model: Origins, Effectiveness, and Applications* (Colorado Springs, CO: BSCS, 2006), http://www.bscs.org/pdf/bscs5eexecsummary.pdf.

47 Michael C. Wittmann and John R. Thompson, "A Course on Integrated Approaches in Physics Education" Newsletter of the Forum on Education of the American Physical Society (Spring 2006), http://www.aps.org/units/fed/newsletters/spring2006/whittmann.html.

48 See, for example, the Sloan Career Cornerstone Center website about Materials Science & Engineering, http://www.careercornerstone.org/matscieng/matscieng.htm.

49 *Materials Science and Engineering at Penn State!*, http://www.youtube.com/watch?v=hVwBTWYwwsg.

50 National Academy of Engineering. *Changing the Conversation: Messages for Improving Public Understanding of Engineering* (Washington, DC: National Academies Press, 2008), http://www.nap.edu/catalog.php?record_id=12187.

51 National Academy of Sciences. Science and Entertainment Exchange, http://www.scienceandentertainmentexchange.org.

2.5 Recommendations

The deliberations of the participants, which are summarized in the previous sections, led to the following recommendations:

- Existing K-12 MSME curricula should be assessed to determine their effectiveness, barriers to adoption and use, and means to overcome those barriers. The MSME community should help develop new or modify existing materials science and materials engineering curricula or curriculum supplements for grades K-12 that fill gaps in existing curricula. They should be versatile so they can be widely used. The curricula must respond to state and national science and technology standards, correspond to best practices regarding how people learn, and address the demands for 21st century skills. They should demonstrate the interdisciplinary nature of materials science and materials engineering and its significant impact on society. Associated assessments should provide evidence for their effectiveness across diverse populations.
- The MSME community needs to encourage science, technology, engineering, and mathematics (STEM) students interested in education to consider K-12 STEM teaching as a profession and to develop the additional skills and knowledge required to become excellent teachers. MSME faculty should consider teacher preparation as an important part of their responsibilities and should work with faculty in education to encourage STEM students to consider K-12 teaching careers in science and math.
- The MSME community must provide training and professional development opportunities for K-12 teachers to improve their knowledge of materials concepts and applications that are relevant to their classrooms. Camps and programs for teachers should be critically assessed, and those that have been demonstrated to be effective should be expanded and more aggressively promoted within the materials community. Both training and subsequent support should be encouraged to ensure that teachers can continue learning and sharing their knowledge with the students. Teachers from diverse backgrounds should be represented in these activities.
- The degree to which K-12 students and teachers are aware of materials related careers and career paths should be determined. The MSME community should create MSME career descriptions using media that are most effective with students, make them available to schools, and assess their impact. Existing MSME education and teacher training programs should include information about MSME careers that teachers can share with students. Outreach tools should show students how careers in MSME play a critical role in modern society.

3. UNDERGRADUATE EDUCATION

3.1 Introduction

As the materials community lays plans for the future of materials education, it must be aware of the evolution of local and national workplaces into global ones. During the workshop session on the future of undergraduate education, participants were asked how to reform materials science and materials engineering education to prepare graduates to remain competitive and lead in this new environment. In addition to having a strong grounding in mathematics, science, and engineering, scientists and engineers will need strong communication and interpersonal skills to work with and lead global teams of their peers. They will need to be cognizant of social, political, economic, and cultural issues as well as be able to function outside their technology-centric environment.[52]

The presentations and discussion emphasized undergraduate educational programs in materials-designated departments (ones with materials science and/or materials engineering as part of their title) rather than materials-related departments (chemistry, physics, mechanical engineering, aerospace, bioengineering, etc.) as the former are responsible for the accredited degree programs and more is known about them. The participants nevertheless recognized the need to understand how the growth of materials options in materials-related departments affects materials education and how the options complement and differ from programs in the designated departments. The presentations at the workshop served as a basis for judging this difference and demonstrated the evolution that has occurred in the undergraduate programs in materials-designated departments.

In addition to mastering the growing knowledge base in materials science and materials engineering, the materials scientist and engineer of tomorrow must gain competency and become skilled in a number of areas. These additional skills are described and discussed in numerous reports and were summarized in the presentation given by Diran Apelian, Howmet Professor of Mechanical Engineering at Worcester Polytechnic Institute. During his presentation Apelian described the engineer of the future as having the following traits:

- *Knows Everything: Can find information about anything quickly and knows how to evaluate and use the information. The entrepreneurial engineer has the ability to transform information into usable knowledge.*
- *Can Do Anything: Understands the engineering basics so that he or she can quickly assess what needs to be done, can acquire the tools needed, and can use these tools proficiently.*
- *Works with Anybody Anywhere: Has the communication skills, team skills, and understanding of global and current issues necessary to work effectively with other people.*
- *Imagines and Can Make the Imagination a Reality: Has the entrepreneurial spirit, imagination, and managerial skills to identify needs, come up with new solutions, and see them through.*[53]

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52 National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (Washington, DC: National Academies Press, 2007), http://books.nap.edu/catalog.php?record_id=11463; National Academy of Engineering, *The Engineer of 2020: Visions of Engineering in the New Century* (Washington, DC: National Academies Press, 2004), http://www.nap.edu/catalog/10999.html; National Academy of Engineering, *Educating the Engineer of 2020: Adapting Engineering Education to the New Century* (Washington, DC: National Academies Press, 2004),http://www.nap.edu/catalog.php?record_id=11338.

53 Diran Apelian. "The Engineering Profession in the 21st Century—Educational Needs and Societal Challenges Facing the Profession." *International Journal of Metalcasting*, (Fall 2007); Gretar Tryggvason and Diran Apelian, "Re-Engineering Engineering Education for the Challenges of the 21st Century" *JOM* (Oct 2006): 14-17; Diran Apelian, "Re-Engineering of Engineering Education—Paradigms and Paradoxes," the Alpha Sigma Mu invited lecture, ASM Fall meeting, Pittsburgh, PA, October 18, 1993 and published in *Advanced Materials & Processes* 145 (6): 110–114.

Although not stated explicitly by Apelian, these same traits are likely to be just as important for scientists to develop.

The challenge for educators is to create a rich and stimulating learning environment that cultivates such a skill set and instills a desire for lifelong learning within a limited and restricted time frame. The workshop participants recognized this challenge and the need for a detailed and focused study. They also considered the suggestion that the materials community follow other engineering disciplines, notably civil engineering, and require a Master's level degree as the entry level to the profession—further discussion on this topic can be found in the section on graduate education.

The factors identified by Apelian and the challenge for educators affect materials science and materials engineering education at a time when the scope is expanding from the traditional areas of metals and ceramics to include polymers, electronic materials, biomaterials, computational materials science and nano-materials. Materials education is also expanding into materials-related engineering (mechanical engineering, civil engineering, electrical engineering, aerospace engineering, chemical engineering, and nuclear engineering) departments and science (physics and chemistry) departments. Because of this expansion, planning for future materials education initiatives must encompass all interested groups.

3.2 Curriculum Development

Kevin Jones, Professor and Chair of the Department of Materials Science and Engineering at the University of Florida, presented the results of a survey of undergraduate curricula in designated materials science and materials engineering departments at the top US universities. In these programs, the distribution of time is divided among mathematics, physics, chemistry, social sciences and humanities, non-materials engineering, and materials science and materials engineering. The distribution for the program at the University of Illinois at Urbana-Champaign is shown in Figure 10; the distribution is similar to that at most other institutions. The materials science and materials engineering component is divided into two sections: materials science and engineering general courses and materials field-specific (metals, ceramics, polymers, electronic materials, biomaterials, etc.) courses. The percentages allocated to each topic in Figure 10, especially in the materials areas are dynamic, not static. For example, the discipline is discussing how to introduce computational materials science into the undergraduate curriculum[54] and the merits of requiring all materials science and engineering students to take biology courses—the challenge is not the importance of the topic, it is finding the time.

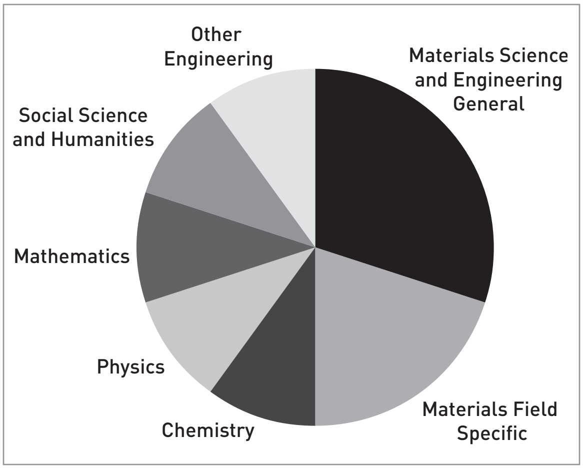

FIGURE 10. *Half of the coursework in the undergraduate curriculum in a materials-designated department is specific to materials science and materials engineering.*

Jones reported that courses beyond traditional thermodynamics, kinetics, and phase diagrams fall on the corners of the materials tetrahedron: synthesis and processing; structure and composition; properties; and application and performance (Figure 11). The differences among programs tend to lie in the number of required and elective courses and the level of emphasis of a particular sub-field; details on these differences can be found in the paper by Cargill and van Tyne.[55] How this balance of courses compares to materials programs or options in materials-related departments remains an open question, although a quick survey of a few departments reveals that the materials course requirement is equivalent to one semester and that many courses appear to be introductory level.

54 National Research Council, *Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security* (Washington, DC: National Academies Press, 2008), http://www.nap.edu/catalog.php?record_id=12199.

55 G. S. Cargill and Chester Van Tyne. "Status and Evolution of Accreditation for Materials Programs in the U.S." (invited paper, "Symposium S -- Materials Education," IUMRS-ICEM2008: International Conference on Electronic Materials, Sydney, Australia, July 29, 2008), http://www.umatcon.org/downloads/082008_IUMRS-ICME2008.pdf.

The diversity in the courses offered by a materials-designated department reflects the degree to which the department broadened from its metallurgy or ceramics roots to materials science and engineering, the number of faculty in the department, and the number of undergraduates. The latter two conditions dictate the number and breadth of the course offerings available to students, especially in their senior year. In departments that fully embraced the transition to materials science and engineering and expanded the faculty to accommodate the new areas, the courses underwent an accelerated shift from vertical, material-specific courses—physical metallurgy, glass technology, ceramic processing, sintering, and so on—to horizontal courses that encompass all material groups.

Some courses are more amenable to this shift than others. For example, Jones explained that his department replaced its introductory courses in metals, ceramics and polymeric/biomaterials with introductory courses in crystalline and molecular materials. Over the last five years, its courses shifted continuously from vertical to horizontal, and such changes are occurring in materials departments nationwide. These changes mean that departments no longer teach some traditional courses despite their technological importance; see for example the National Research Council report *Assessment of Corrosion Education*.[56] The transformation of faculty expertise as departments broaden their research scope exacerbates the situation. The participants noted that utilizing expertise at other universities and employing Internet technologies to deliver the content nationwide are possible mechanisms to counter this trend and to offer critical traditional courses. These methods, of course, would require institutional change so that credit earned at one institution would apply to a degree program at another.

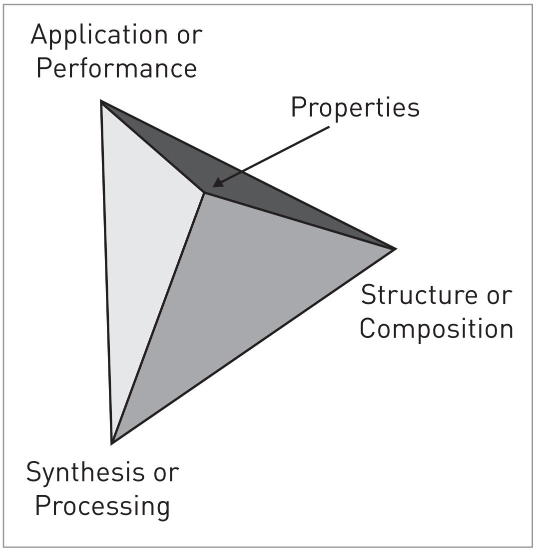

FIGURE 11. *Each corner of the materials tetrahedron shows one component of materials science and materials engineering education in a materials-designated department.*

According to the survey across top universities, all programs in materials-designated departments retain strong laboratory components with a senior or capstone design course as required by the Accreditation Board for Engineering and Technology.[57] As changes are made to the undergraduate curriculum, faculty must be aware of the career paths of undergraduates and how the shift to more horizontal curricula affects employment opportunities. Approximately half of the undergraduates earning a baccalaureate degree traditionally seek employment in industry, and the other half seek advanced degrees, although increasingly more pursue advanced degrees outside the field.

The course curriculum is very different in materials-related science and engineering departments, which usually offer a limited number of materials courses emphasizing materials issues related to the core discipline or are predominantly introductory or survey courses. The direction of course content raises the interesting possibility that the next generation of materials scientists and engineers might receive degrees in one of these fields and minor in just one of the sub-specialties of materials science. If materials education is a secondary priority, the possibility that a materials scientist or materials engineer might not understand phase diagrams or be able to identify the primary constituents of steels becomes more probable. This situation raises the following questions: What should be the minimum core knowledge expected for someone with the title of materials scientist or materials engineer? Is it possible for the materials community to define such a minimum? Do materials-designated departments provide a sufficiently distinct educational background and experience to justify their continuance? These questions were raised but not answered in the workshop.

56 National Research Council, *Assessment of Corrosion Education* (Washington, DC: National Academies Press, 2009), http://www.nap.edu/catalog.php?record_id=12560.

57 ABET, Inc., http://www.abet.org. Of all the departments offering a baccalaureate degree in materials science and engineering, only two are not accredited by ABET—the standouts are Rice University and Stanford University.

3.3. Recruiting and Retaining Students in MSME

Attracting students into the field has been a perennial problem for MSME-designated departments. The low flow of students is attributed in part to lack of awareness of the field and the continuing lack of interest in science and engineering in general. Recommendations to address materials education and career awareness in kindergarten through 12th grade are considered in section 2. What can be done and what is being done to attract and retain undergraduates in materials science and materials engineering are important questions.

Workshop participants noted that several designated departments initiated successful programs to increase their undergraduate enrollment. The University of Pennsylvania capitalized on the excitement about nanoscience and nanotechnology, leading to the development of a curriculum that concentrates on nanoscience. Close inspection of the program, however, determined that topics covered still reside within the confines of the materials tetrahedron and that essentially the same material is covered as in most materials science and engineering departments. The strategy has been successful nevertheless, resulting in a five-fold increase in undergraduate enrollment.

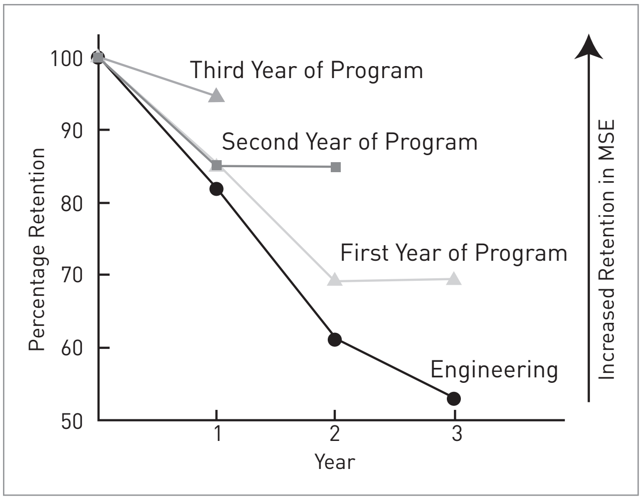

FIGURE 12. *The undergraduate research experience program increases the retention of students in materials science and engineering at the University of Florida. The program has been in operation for three years and shows an increasing retention rate with each year.*

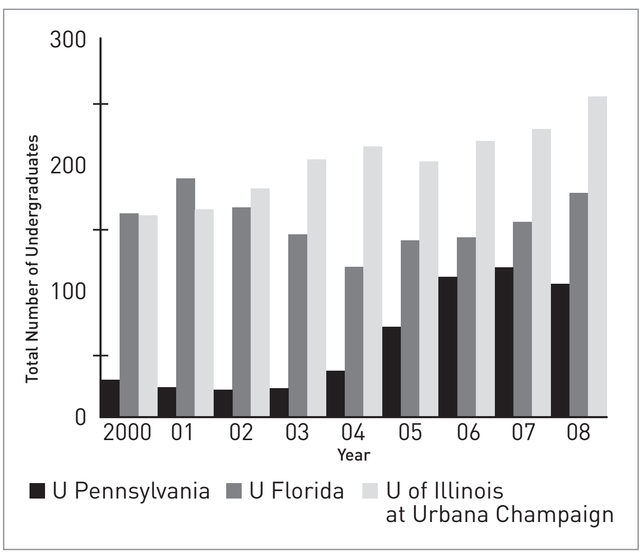

FIGURE 13. *Growth in total undergraduate populations in materials science and engineering departments due to different recruitment strategies.*

Others have employed different marketing strategies. The University of Illinois at Urbana-Champaign contacts students and invites them to attend an Open House at which prospective students discover the exciting and crucial role the field plays in providing technical solutions to societal problems. The message demonstrates the difference people can make in the world with a degree in materials science and engineering. The Illinois program reports a high success rate in enrolling students if they attend this recruitment event—the Illinois program now has 280 students throughout the four years, making it the largest program in the nation.

Efforts at other institutions concentrate on retaining students. At the University of Florida, for example, undergraduate freshmen are involved in research programs. The purpose is to engage the students and show them how a degree in materials science and engineering will enable them to make a difference. The program is new, but the increases in student retention with each year of operation are encouraging, see Figure 12.[58] Overall impact of each of these different strategies on the number of undergraduates in the materials science and engineering is compared in Figure 13.[59]

Although not discussed at the workshop, an important and overlooked topic that emerged during review was educating non-engineering and non-science students about materials science and engineering. Such courses, if delivered properly and with appropriate expectations, can serve to reintroduce

58 Information provided by Professor K. Jones, Chair of Materials Science and Engineering, University of Florida.
59 Information provided by Professor K. Jones, University of Florida; Professor P. Davies, University of Pennsylvania; and Professor I. Robertson, University of Illinois.

students to science and engineering, introduce scientific and engineering principles and problem solving methods, and perhaps rekindle some of the interest lost in high school science courses. Examples of such courses do exist at several universities with one example being the course MSE 101 Materials in Today's World offered at the University of Illinois at Urbana-Champaign,[60] another being EAS 210 Introduction to Nanotechnology offered at the University of Pennsylvania.[61]

It is appreciated and acknowledged that this section is materials science and engineering department and program centric. This was necessary as this group provides the most information about undergraduate programs that could be accessed, and it should serve as the foundation for the development of undergraduate materials program in other engineering and science departments. It also demonstrates what is different between programs in designated departments and ones in materials-related departments. The participants recognized that materials-related departments and programs have a critical and vital role to play in not only defining the core body of knowledge that a materials scientist and materials engineer should know but in helping develop and teach the curriculum. This broadening must happen and it is suggested that the University Materials Council[62] undertake the task of ensuring it does through active engagement of the other disciplines.

3.4 Recommendations

The deliberations of the participants, which are summarized in the previous sections led to the following recommendations:

» The broad-based materials community should seek funding for a National Academies study on the current status of and future needs for materials education in the USA. National concerns for ensuring security and continued economic growth, as well as sufficient energy and fresh water supplies in an efficient and sustainable manner, should motivate the study. How to prepare materials students to address these concerns needs to be evaluated using a global context, recognizing the changing character of materials development, research, and manufacturing.

» Curriculum revision should seek novel ways to include biology, business, project management, leadership, entrepreneurship, and international experiences into undergraduate education. Educators should explore a variety of implementation strategies. The University Materials Council, the council of the heads and chairs of materials science and engineering departments and programs nationwide, should assess ongoing curriculum revision in departments across the country and disseminate best practices.

» MSME educators should consider online educational programs to continue teaching traditional materials areas as faculty expertise in these areas is lost and these courses are displaced to accommodate ones in emerging areas. This medium might be especially beneficial at smaller schools and for granting continuing education credits.

» To attract more students to the discipline, materials programs should change the message used to engage prospective undergraduates. The discipline is an enabling one and one that has the potential to provide technological solutions to critical societal issues. This type of message needs to be used to excite students about opportunities in the field.

» Research, internship, and industrial experiences, both domestic and foreign, are important for the preparation of future materials scientists and engineers. Undergraduate students need research experiences even as early as the freshman year.

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60 University of Illinois at Urbana-Champaign, Materials in Today's World, http://courses.illinois.edu/cis/2009/fall/catalog/MSE/101.html?skinId=2169.

61 University of Pennsylvania, Introduction to Nanotechnology, http://www.seas.upenn.edu/mse/ugrad/undercourses.html.

62 University Materials Council is comprised of the heads and chairs of materials science and engineering departments in North America. Information can be found at http://www.umatcon.org/.

4. GRADUATE EDUCATION

4.1 Introduction

In the National Academies report Reshaping the Graduate Education of Scientists and Engineers, *the Committee on Science, Engineering, and Public Policy recommended that materials science and materials engineering education prepare graduates for the interdisciplinary, collaborative, and global 21st century marketplace.*[63] *This need is reinforced by reports such as* Globalization of Materials R&D: Time for a National Strategy, *which was conducted by the National Research Council's National Materials Advisory Board.*[64] *This report reached the conclusions that:*

- *The globalization of MSE R&D is proceeding rapidly, in line with broader trends toward globalization. As a result of increasing international trade and investment, the emergence of new markets, and the growth of the Internet and the global communications system, MSE R&D in the United States is an internationalized activity with a diverse set of international partners,*
- *The globalization of MSE R&D is narrowing the technological lead of the United States.*

Regarding education, the report concluded that "The MSE education system, including K–12 mathematics and science education, will have to evolve and adapt so as to ensure a supply of MSE professionals educated to meet U.S. national needs for MSE expertise and to compete on the global MSE R&D stage. The evolution of the U.S. education system will have to take into account the materials needs identified by the federal agencies that support MSE R&D as well the needs of the materials industry."

Although these reports identified the challenges our graduate education system must address, they did not make concrete recommendations for how programs must evolve to meet the challenges. During the session on graduate education, the participants identified interdisciplinary research and career preparation coursework as two areas in which improvements could and should be made. They also acknowledged that curricula and administrative changes alone are insufficient and that students should have access to experiences that teach them the broader skills they need to diversify their capabilities and build viable life-long careers in materials science and materials engineering.

To provide a background for the workshop discussions, Susan Sinnott, Professor of Materials Science and Engineering at the University of Florida, presented a comparison of the coursework requirements in the US News and World Report top ten materials science and engineering designated departments in the United States and survey data about the graduate student population in designated programs. She suggested that perhaps an alternate and more holistic approach to graduate MSME education is needed. Wendy Cieslak of Sandia National Laboratories outlined a possible role the national laboratories could play in changing graduate education through efforts such as the National Institute for Nano-Engineering.[65]

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63 National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Reshaping the Graduate Education of Scientists and Engineers* (Washington, DC: National Academies Press, 1995), http://www.nap.edu/openbook.php?record_id=4935.

64 National Research Council, *Globalization of Materials R&D: Time for a National Strategy* (Washington, DC: National Academies Press, 1995), http://books.nap.edu/openbook.php?record_id=11395&page=R1.

65 The National Institute for Nano-Engineering (NINE) is a government/university/industry collaboration formed to develop the next generation of innovation leaders for the U.S. by involving students in large scale multi-disciplinary research projects focused on developing nano-enabled solutions to important national problems. NINE addresses a growing national concern: that America's science and engineering education and innovation engine is in danger.

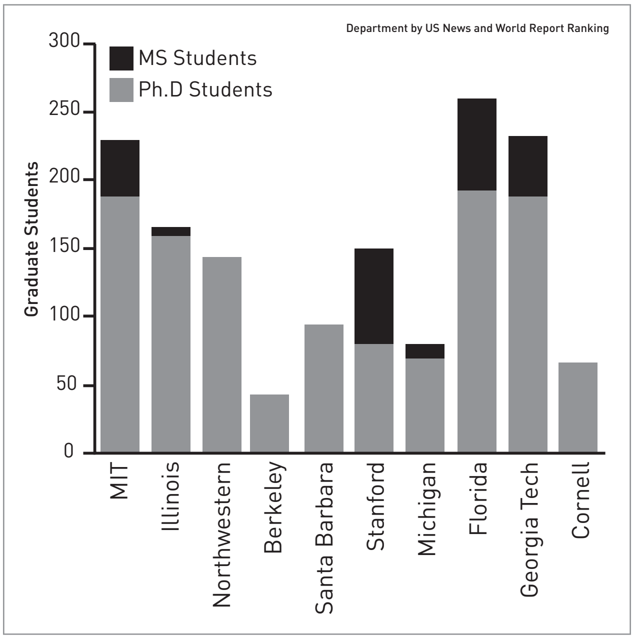

FIGURE 14. *Nearly all the top ten materials science and engineering departments in the United States enroll more doctoral students than Master's students.*

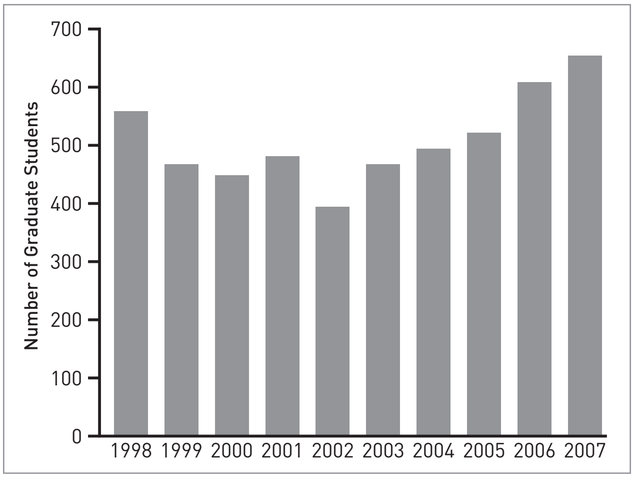

FIGURE 15. *Number of PhDs awarded in materials science and engineering from designated departments.*[66]

To address the number of students being awarded an advanced degree in materials science and engineering from the designated departments, Sinnott compared the number of graduate students in Master's and doctoral degree programs options at the top ten departments (Figure 14). With the exception of the program at Stanford, the data show the majority of departments enroll a greater number of PhD than Master's degree students. The total number of doctoral MSME degrees awarded by all designated departments as shown in Figure 15 has recovered from a low of 396 in 2002 to a ten-year high of 679 in 2007.[66] *Similar data was not available for the materials-related programs. However, the National Academy of Sciences report* Manpower and Education in Materials Science and Engineering *noted that the largest number of workers in the materials science field were trained in chemistry (44%), followed by materials science and engineering (39%) and then by physics (16%).*[67] *This data triggered the question: how many graduates should the institutions educate and train given the number of positions available at academic research institutions, national laboratories, and industry? Here the presentation by Cieslak provided a partial answer as she described qualitatively the age distribution of employees at Sandia National Laboratories and the need to find replacements as the baby-boomers reach retirement age (Figure 16).While this situation certainly holds at many other places, it has to be balanced against the shift to a global research and development arena.*

Another topic raised was the diversity of the students seeking advanced degrees in MSME. Sinnott provided the workshop participants with a snapshot of the participation of minorities in Department of Materials Science and Engineering at the University of Florida, Figure 17. The total number of under-represented students in the program at Florida is about 10% of the students in the department. Unfortunately, these numbers exceed those at most other institutions. Clearly, a challenge for the MSME community, and science and engineering in general, is to increase the number of under-represented minorities, women and people with disabilities; several workshops have been held to increase awareness and promote strategies for attracting and retaining more from this group to science and engineering.[68]

66 Jaquelina C. Falkenheim and Mark K. Fiegnener, "2007 Records Fifth Consecutive Annual Increase in U.S. Doctoral Awards," *Science Resource Statistics—Info Brief* (Arlington, VA: National Science Foundation, Nov 2008), NSF-09-307, http://www.nsf.gov/statistics/infbrief/nsf09307/.

67 National Research Council, "Chapter 5: Manpower and Education in Materials Science and Engineering" in *Materials Science and Engineering for the 1990s: Maintaining Competitiveness in the Age of Materials* (Washington, DC: National Academies Press, 1989), http://www.nap.edu/openbook.php?record_id=758&page=143.

68 For example, see the workshop reports *Gender Equity: Strengthening the Physics Enterprise in Universities and National Laboratories*, http://www.aps.org/programs/women/workshops/gender-equity/upload/genderequity.pdf; *Workshop on Building Strong Academic Chemistry Departments Through Gender Equity*, http://www.seas.harvard.edu/friend/GenderEquity_report+cover.pdf; and *Gender Equity in Materials Science and Engineering*, http://www.matse.illinois.edu/gender/GEWreport.pdf.

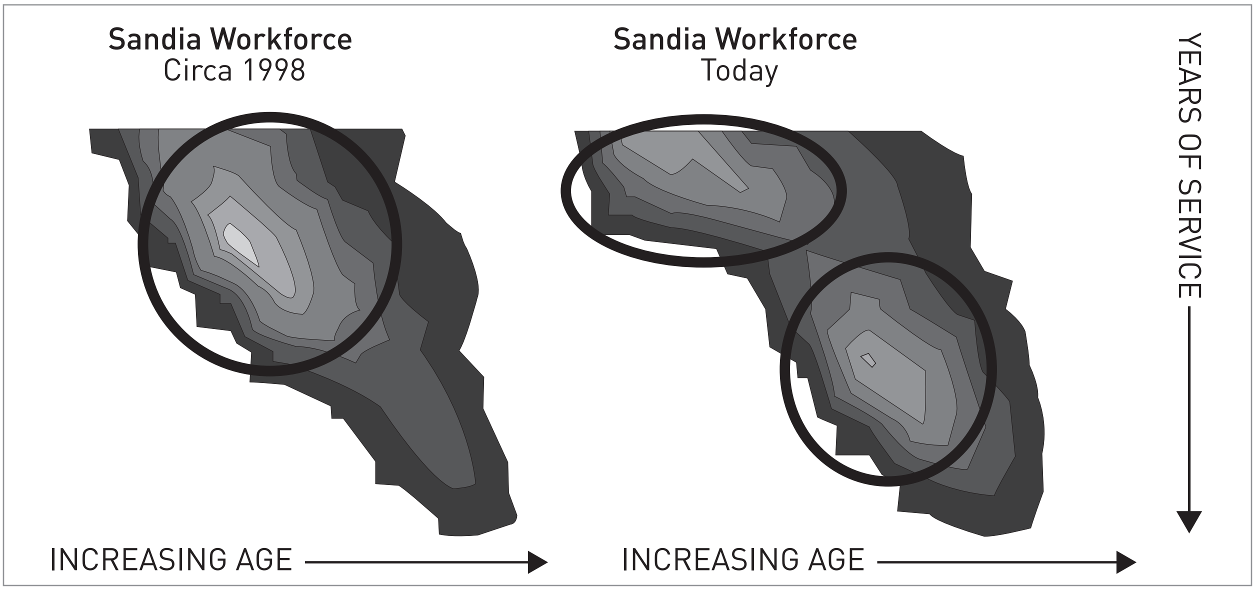

FIGURE 16. *In 1998, almost all the workforce at Sandia National Laboratories was 30-55 years old. Now, baby-boomers are starting to retire and and an influx of younger workers is starting to replace them. Shading illustrates the number of workers with lighter shades indicating more workers. The two graphs share the same shading scheme.*

4.2 Course Curriculum

Workshop participants asked how to prepare students in MSME Master's and doctoral programs such that they are prepared to contribute to the increasingly interdisciplinary, collaborative, and global work place. Students pursuing MSME advanced degrees in designated departments enter with baccalaureate degrees from a variety of undergraduate programs, including materials science and engineering, other engineering and science fields, mathematics, and sometimes applied social sciences and humanities. It was not evident that this cross-fertilization was occurring in the materials-related departments. Furthermore, degrees in the specialization of materials are conferred by both materials-designated and materials-related departments with the consequence that a MSME graduate may have exposure to just one sub-field of the discipline (polymers, materials chemistry, metals) and have little to no knowledge of the others. This point raised some interesting questions:

> What should be the minimum core materials knowledge base expected of all Master's and doctoral MSME degree holders?
>
> and
>
> Is it possible to reach consensus of what topics would constitute the core knowledge base?

The latter question was seen as a particularly challenging issue because of the number and diversity of stakeholders.

The participants felt that the wide range of MSME graduate programs that exist nationwide makes identifying and prescribing a set of common core concepts challenging

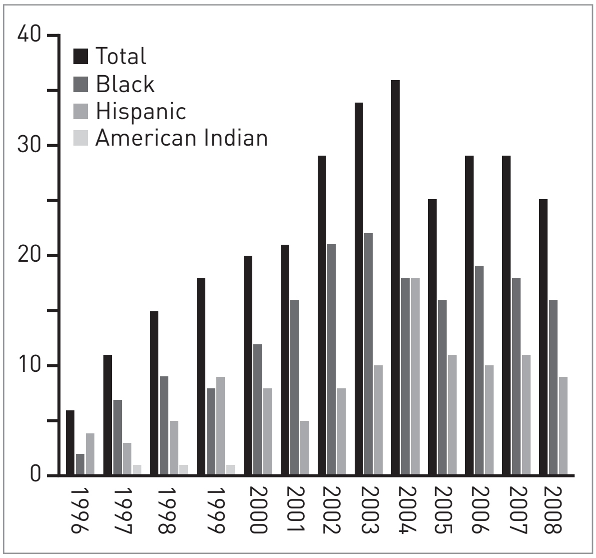

FIGURE 17. *The participation of underrepresented minorities in the Department of Materials Science and Engineering at the University of Florida has fluctuated in the past 10 years. The total number of underrepresented students is equivalent to about 10% of the student population.*

Materials-Designated Departments

The fundamental core classes in materials-designated departments include:

- Structures
- Kinetics
- Properties
- Thermodynamics
- Processing

Sinnott's survey of programs from Illinois, Michigan, Berkeley, MIT, Northwestern, Stanford, Cornell, Florida, Georgia Tech, and Penn State revealed the following:

- Seven of the 10 departments have required core classes.
- The number of classes in the core ranges from one to 10.
- Most students take additional classes outside the core. The courses selected are determined by students' research interests.
- Several departments require or recommend students who do not have materials background take an accelerated introductory-style course.

Materials Chemistry Programs

- University of Illinois at Urbana-Champaign curriculum includes two core courses (Advanced Materials Chemistry and Physical Methods in Materials Chemistry) and an additional three from a list provided by the department.
- University of Wisconsin-Madison curriculum includes three required courses (Chemistry of Inorganic Materials; Chemistry of Organic Materials; and Materials Chemistry of Polymers, which may be substituted for another from an approved list).

FIGURE 18. *A comparison of coursework for materials science and materials engineering degrees from materials-designated departments and for materials chemistry degrees from chemistry departments shows that departments require different numbers and types of classes.*

and perhaps unattainable. Faculty expertise, student composition, and institutional relationships define each department or program and its unique areas of interest. In addition, traditional departments or programs that produce materials science specialists such as chemistry, physics, chemical engineering, electrical engineering, bioengineering, materials science and engineering, and other departments each have their own set of core concepts and have decided the appropriate breadth and depth of courses for their students. However, the disparity between the minimum number of discipline-specific courses required even within materials-designated departments is great and even greater when broadened to include options in materials-related departments. For example, the data presented in Figure 18 compares the core course requirements in the nation's top materials-designated departments and in two materials programs in chemistry departments. Three of the ten materials-designated departments examined do not require any core courses and within those that do require students to take a set of core courses, the number required varies from one to ten. This suggests that even in the designated-departments there is not a consensus as to what constitutes the core knowledge base. This may reflect the difference in the breadth and emphasis of the research conducted in these departments. Interestingly, in many materials-designated departments it is recommended or required that students who do not have a MSME background take an accelerated introductory-type course. The remainder of the coursework requirements is satisfied through coursework selected to benefit the student's research program. In contrast, from a very restricted survey of materials chemistry programs, it is seen that fewer courses in the specialization are required and those required remain chemistry centric. No program emphasizes courses outside the discipline that could provide students with the other skills they will need during their careers.

Despite this disparity in core knowledge base, the workshop participants recognized that as the career paths of students vary considerably and many change paths during their careers, a core knowledge base and skill set is critical for defining the distinctiveness of a materials science and materials engineering graduate. Additionally, the coursework offered in academic departments must offer a process for students to grow adept in the knowledge and skills of the materials fields that they will need for the future. Each MSME graduate must also be prepared for the lifelong learning necessary to stay current and relevant in a constantly changing MSME world. An interesting suggestion to overcoming the lack of a well-defined core knowledge base was to redefine graduate education in the discipline, recognizing that it is multi- and inter-disciplinary and to adopt a more holistic approach. Such a transformation would require institutional modification in terms of allocation and accounting of resources, funding as well as faculty time, the variable areas of faculty specialization, and the promotion and tenure process. MSME departments might find partial solution through intra- and inter-departmental collaboration, team teaching involving not just faculty from the same department, and cross-listing of courses. These approaches have resulted in changes at some institutions. For example, at the University of Minnesota-Twin Cities cooperative efforts among materials faculty led to the chemistry department offering materials chemistry courses, and at University of Texas-Austin, students from all science and engineering disciplines populate graduate nanomaterials courses. These approaches would enable MSME departments to increase the number of graduate students as well as to expand the range and quality of materials-related research and education.

There has been increasing demand in some engineering disciplines to make a Master's level degree the entry point to the profession. This is in recognition of the increase in material that must now be covered in all disciplines to prepare to students to meet the demands of their profession. Civil engineering has already made this change and others are likely to follow. With this change comes the need to accredit and certify the new degree programs, and within engineering this most likely will fall within the purview of ABET. Workshop participants discussed how this change and the resultant certification would impact materials science and materials engineering programs. Following discussion they concluded that certification of Master's level graduate programs by outside accrediting organizations was neither warranted nor viable because no single certifying agency is fully engaged with all aspects of a modern materials science and materials engineering curriculum. Furthermore, the attraction of students from a range of engineering and science disciplines makes it impractical to master a common body of knowledge in a reasonable time. Certification could jeopardize the diversity of MSME programs that encompass the broad range of materials engineering, research, applications, and performance.

4.3 Interdisciplinary Training

MSME graduate students can tackle some of the most interesting questions and learn about innovative engineering solutions by engaging in interdisciplinary research. Students who use knowledge and techniques from all science and engineering fields, including social sciences and humanities, have the ability to evaluate, design, improve, and fabricate unique materials. Examples of university and federal interdisciplinary programs do exist, but incorporating interdisciplinary research and training throughout graduate materials education requires a change in academic culture and must occur without significantly increasing the students' time to degree completion.

Traditional academic resource allocation often impedes the development of interdisciplinary courses and programs that span disciplines and departments, schools, and colleges. The basis for traditional academic administration is a departmental unit. This structure heavily influences faculty and staff behavior by fostering vertically integrated teaching and training efforts that do not assimilate ideas from other disciplines or departments. Researchers and instructors are reluctant to participate in interdisciplinary activities when evaluations of faculty and academic units do not account for these activities. Untenured faculty members are especially at risk if the evaluation system does not properly account for their interdisciplinary accomplishments.

Workshop attendees identified a number of strategies to incorporate interdisciplinary research and training into the academic infrastructure of MSME programs. One strategy is to develop courses that fully integrate multidisciplinary knowledge and cross-list them across the relevant disciplines. Another is to expose first and second year graduate students to a broad range of research options through intra-departmental and inter-departmental research rotations. Such rotations will help students and faculty members identify common interests and potential collaborative research areas and allow students to make more informed choices about research advisors. Rotations might not be practical for all MSME programs since their graduate students are typically supported entirely by externally funded research assistantships. And graduate students interested in pursuing materials-related research in physics and chemistry departments have heavy course loads and teaching assistant duties in the first year that preclude time in the laboratory. Increasing the number of externally funded fellowships for MSME graduate students would provide the flexibility to accommodate research rotations.

The interdisciplinary nature of MSME-designated departments is reflected in the educational backgrounds of the faculty members they hire. At most of the top institutions, the MSME faculty members have degrees in metallurgy, ceramics, materials, chemistry, chemical engineering or physics. This interdisciplinary environment is further enhanced through affiliate or courtesy appointments for faculty members in other science and engineering departments who have an interest in MSME research. For example, the Department of Materials Science and Engineering at Cornell University weaves faculty efforts among multiple departments to create an interdisciplinary environment. The department consists of faculty housed in the Department of Materials Science and Engineering and "field" faculty housed in other STEM departments. The faculty body is composed of more than forty people affiliated with three colleges and ten departments. The graduate programs in the department require Master's and doctoral students to complete a core curriculum of materials chemistry, mechanical properties, thermodynamics, kinetics, electronic properties, and structure. Graduate students are also required to have two minor specializations, one of which must be outside of materials science and engineering.

The Applied Physics doctoral program at the University of Michigan is another interdisciplinary program, which integrates the physical sciences within the College of Literature, Science, and the Arts and the College of Engineering. Doctoral students take core courses in their first two semesters followed by advanced courses in their chosen specialization. Advanced course options include chemistry, materials science and engineering, mathematics, nuclear engineering, and physics. And the University of Massachusetts Amherst utilizes architecture to promote interdisciplinary culture: the Integrated Sciences Building clusters the life and chemical sciences in the same building. It houses undergraduate chemical and upper division life science teaching laboratories along with flexible research space, promoting interdisciplinary research.

Other examples that foster multi- and interdisciplinary research can be found in the research centers and institutes that are already on many campuses. For example, the Beckman Institute at the University of Illinois at Urbana-Champaign has a mission to develop collaborations between engineering and the life sciences, the Beckman Institute at the California Institute of Technology fosters interactions between chemical and biological sciences, and the one at the University of California-Irvine is an interdisciplinary center for Biomedical Optics. Similarly, the Materials Research Laboratories and Institutes at the University of Illinois and Pennsylvania State University have served as vehicles for coordinating and catalyzing materials research across their respective campuses. These institutes, centers and laboratories serve to dissolve the barriers that often exist and prohibit faculty collaborations across departments and colleges. These may provide a mechanism for establishing a new model for graduate programs in which a holistic as opposed to the current discipline-centric approach is adopted.

A national investment in interdisciplinary education takes the form of the NSF Integrative Graduate Education and Research Traineeship (IGERT) program.[69] It fosters curricular modification and programmatic design for interdisciplinary education and research training for graduate students (see text box on next page). The IGERT program trained 4890 students from 1998 to 2008. Workshop participants expressed concerns about the program. Some said the finite duration of the funding is a barrier to a larger, long-range effect on the graduate curriculum. However, this suggests that individual efforts are perhaps not fulfilling the original mission and requirement of IGERT sponsored efforts, which is to have the institutional commitment to programmatic changes founded and enabled by IGERT support. The required institutional support for an IGERT project and the cost of sustaining a program beyond the project period is prohibitive, and the low cost-of-education allowance for student tuition and health insurance makes IGERT projects impractical at many institutions. Individual faculty members expend significant time and effort in addition to maintaining their existing responsibilities, yet in some situations, traditional departments do not recognize interdisciplinary activities. Despite these concerns, workshop participants said that IGERT materials-related projects are advantageous for recruitment. The student stipend

69 National Science Foundation, Integrative Graduate Education and Research Traineeship Program, http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=12759.

IGERT Synopsis

"The Integrative Graduate Education and Research Traineeship (IGERT) program has been developed to meet the challenges of educating U.S. Ph.D. scientists and engineers who will pursue careers in research and education, with the interdisciplinary backgrounds, deep knowledge in chosen disciplines, and technical, professional, and personal skills to become, in their own careers, leaders and creative agents for change. The program is intended to catalyze a cultural change in graduate education for students, faculty, and institutions, by establishing innovative new models for graduate disciplinary boundaries. It is also intended to facilitate diversity in student participation and preparation, and to contribute to a world-class, broadly inclusive, and globally engaging science and engineering workforce."

National Science Foundation
http://www.nsf.gov/crssprgm/igert/intro.jsp

is high, and such projects provide innovative and formal interdisciplinary research and training experiences. Some workshop participants suggested that Nanoscale Science and Engineering Centers and Materials Research Science and Engineering Centers must take a leadership role in facilitating implementation of interdisciplinary materials curricula. This will have to be done in partnership and with the support of the academic units as well as the university.

4.4 Career Preparation

Some of the most important skills that prepare graduates for their careers might not be learned from a science or engineering textbook. To prepare students for all aspects of their careers, universities offer a wide range of classes, expert guidance, programs, and study materials helpful before and after graduation. Topics include writing skills, scientific ethics, oral communication, presentation skills, mentoring, project management, teamwork and leadership skills, data management, entrepreneurial initiatives, and international experiences. Some, such as communication skills and ethics training, are widely viewed as crucial elements of career training, while others are more individualized. Career advice and development is an ongoing process throughout a student's and a professional's life.

Workshop participants said that materials educators could teach students vital career skills by incorporating activities into research and graduation requirements. Teaching assistants can learn communication skills on-the-job while talking and listening in the classroom, and students writing the first draft of publications are preparing to be active in the research community. Qualifying exams and the thesis proposal are an opportunity to discuss complex topics with their peers. Writing research proposals builds critical thinking and communication skills and prepares students for the research proposals that they will write during their careers, both in universities and in industry. Encouraging students to take internships at the right time in their education is another opportunity for them to develop life-long learning habits.

Flexible and adaptive programs also give students the chance to be involved in guiding their graduate training and career preparation. Universities need to set specific requirements and provide a range of opportunities from which students can select training according to their individual career goals. However, graduate students should be guided appropriately so that the time to degree completion remains reasonable.

Students might develop skills for their careers through mentoring. Coursework, required activities, and exams set a framework for students' education, but they might not provide the tacit knowledge that students need to succeed. Establishing relationships with more experienced members of the field helps students navigate their career paths. Individuals from business, national laboratories, or international institutions who present colloquia or talk with students informally about their experiences mentor students in a way not easily found in an academic setting. Mentors who are faculty members but not the student's primary research advisor can also be important guides.

Graduate students can be excellent mentors for high school and undergraduate students, while learning communication, team building, and leadership skills. The National Science Foundation-funded Graduate STEM Fellows in K-12 Education program offers an excellent opportunity for graduate students to mentor young people. The graduate students benefit from reflecting on their own experiences and working with others. Seminars about mentoring, which are relevant whether the graduate student is giving or receiving mentoring, can support productive interactions that can benefit all stakeholders.

Entrepreneurship is another area for student exploration. Job opportunities in small companies and starting new business areas in large companies (intrapreneurship) require that students understand start-up development and the business world. One example of how these subjects can be introduced is the University of Wisconsin-Madison Entrepreneurial Bootcamp (WEB).[70] This camp exposes graduate students in science and engineering to a one-week intensive training camp and teaches them about intellectual property, small business financing, and business models. Managerial skills learned in WEB help prepare graduate students for their future careers in industry and in national laboratories, even if they do not become entrepreneurs.

International experiences can significantly broaden a student's perspective of the world. The National Science Foundation's Materials World Network and the Office of International Science and Engineering both fund international experiences and research.[71] Faculty members who have NSF research grants can also apply for a supplement that can finance an international experience for their graduate students.

4.5 Recommendations

The deliberations of the participants, which are summarized in the previous sections, led to the following recommendations:

- » A benchmarking study of the current state of MSME graduate education should be undertaken with the goal of determining the breadth and depth within the various programs. The outcome of this study could serve as the foundation for the MSME community to define a common core body of knowledge. At a minimum, it is recommended that all graduate programs in materials science and materials engineering define the mission and goals of their MSME degree program. The core principles should be inclusive of the relationships between (1) structure, (2) property, and (3) processing, and (4) application/performance of materials.
- » Materials science and materials engineering Master's programs should not be externally certified. This recommendation reflects the diversity of the study body pursuing MSME as well as the range of engineering and science departments offering such degrees.
- » Academic policies and procedures need to incorporate and sustain interdisciplinary research and training into materials science and materials engineering graduate programs. Interdisciplinary activities include inter-departmental and intra-departmental activities such as developing interdisciplinary courses, creating interdisciplinary degree programs, and creating interdisciplinary faculty appointments to meet the expanding academic and career needs of materials science and materials engineering graduates.
- » The MSME community should consider if the discipline-centric approach to graduate education is providing the best education and training for our students or if it is time for a different educational model, perhaps one that takes a more holistic approach, to be developed and implemented.

70 University of Wisconsin, Wisconsin Entrepreneurial Bootcamp, http://www.bus.wisc.edu/weinertcenter/Web.asp.

71 National Science Foundation, Materials World Network, http://www.materialsworld.net/; National Science Foundation, Office of International Science and Engineering, http://www.nsf.gov/div/index.jsp?div=OISE.

5. CROSS-CUTTING THEME: USE OF INFORMATION TECHNOLOGY IN MSME EDUCATION AND RESEARCH

During the discussions in each section, one theme permeated all, namely, the increasing use of the Internet as a resource of information, a communication and education tool. Online courses, digital libraries, simulations and animations, the Internet, and open-source media constitute forms of information technology (IT) that are increasingly important components of MSME education and training. The judicious use of information is paramount. With trusted information, IT equips students and learners to access information regardless of their physical location and enables teachers to develop new educational tools.

Workshop participants cautioned that controlling the quality of information is critical for the reliable use of networked resources and that quality control should limit how information is used. Students should be aware of the difference between peer reviewed information and information simply posted on the World Wide Web. As information becomes readily available on the Internet, ethics training becomes even more important in materials science and materials engineering education.

Materials educators, professionals, and students currently have access to electronic resources such as the Materials Digital Library and the comPADRE Pathway, both part of the National Science Digital Library[72]; ASM International e-courses, webinars, and self-study courses;[73] The Minerals, Metals, & Materials Society (TMS) Knowledge Resource Center;[74] and materials selection tools such as CES EduPack.[75] The IGERT programs have standards of best practices that might serve as models for further development of IT resources, possibly through the efforts of professional societies.

In addition to providing immediate content to users, IT and online education can reach a network of people who might not have access to traditional venues. IT is a vehicle to enhance the number and diversity of students entering materials fields. For example, the diverse student population of community and two-year colleges might engage in software-based MSME experiences or taking introductory level courses. Simulations, animations, and modular software packages are novel tools to increase interest in materials. Students might become sufficiently excited and interested to pursue more advanced degrees. Online courses and online degrees—when appropriate and when articulation barriers dissolve—can reach students in remote locations or who cannot travel. Continuing education students can similarly benefit.

IT resources also provide graduate students, as well as working scientists and engineers, with the opportunity to learn information at their own pace, anytime it is convenient for them. Courseware available free to the public, such as the Massachusetts Institute of Technology Open Courseware site is a valuable resource for self-instruction.[76] Interactive information tech-

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72 National Science Digital Library, http://www.nsdl.org; comPADRE, http://www.compadre.org; Materials Digital Library, http://matdl.org/repository/index.php.

73 ASM International, Education & Training, http://asmcommunity.asminternational.org/portal/site/www/Education/.

74 TMS, Knowledge Resource Center, http://knowledge.tms.org/home.aspx.

75 Granta Material Intelligence, CES 2009 Edupack, http://www.grantadesign.com/.

76 Massachusetts Institute of Technology, Open Courseware, http://ocw.mit.edu/.

nology might bridge the disciplinary divide between graduate students in materials science and engineering departments and other departments.

Educators might also consider using the very people they are educating to contribute to the teaching effort. Crowd-sourcing techniques such as wikis might improve courseware and encourage cohort-teaching, making teaching and learning an interactive process. The novel ideas and activities imagined by one student can be shared with many others.

6. WORKSHOP PROGRAM

Program: Workshop on the Future of Materials Science & Materials Engineering Education
September 18-19, 2008 at the Holiday Inn Ballston in Arlington, Virginia

THURSDAY, SEPTEMBER 18, 2008

8:10-8:20 am	Welcome remarks by Zakya Kafafi, NSF Division Director, Division of Materials Research (DMR), Mathematical and Physical Sciences Directorate
8:20-8:30 am	Welcome remarks by Joan Ferrini-Mundy, NSF Division Director, Division of Research on Learning in Formal and Informal Settings (DRL), Education & Human Resources Directorate
8:30-9 am	Keynote Speaker Cherry Murray, Lawrence Livermore National Lab “Materials Science & Engineering U.S. Competitiveness”

Session 1 Undergraduate Education for the Materials Scientists and Engineers of the Future
Session Chair: Ian Robertson; Scribe: Laura Bartolo

Goals: Discussions related to the future core of a modern materials science and engineering (MSE) education at the undergraduate level, especially across materials-designated and materials-related programs, how to provide effective interdisciplinary training to MSE undergraduates across various departments, and how to prepare them for the demands of globalization of MSE and need for adaptability and innovation

Anticipated Outcome: Strategies for improving MSE education for undergraduates across different departments

9-9:30 am	Diran Apelian, Howmet Professor of Mechanical Engineering, Worcester Polytechnic Institute. “Educating the Materials Scientists and Materials Engineers of 2020”
9:30-10 am	Kevin Jones, Materials Science and Engineering, University of Florida. “What Constitutes a Modern Materials Science and Engineering Undergraduate Program?”
10-11am	Breakout sessions
11:30 am-12:30 pm	Breakout session reports followed by open discussion Moderator: Laura Bartolo; Scribe: Warren Collins

Session 2 Engaging K-12 students and teachers in Materials Science Education
Session Chair: Larry Woolf; Scribe: Rob Thorne

Goals: Discussions related to the need for, importance of, and methodology for introducing materials science and engineering concepts to K-12 students

Anticipated Outcome: Strategies for introducing MSE education at the K-12 level

1:30 pm-2 pm	Philip Sadler, Department of Astronomy, Harvard University. "Relating Precollege Experiences and Undergraduate Science Interest and Performance"
2 pm-2:30 pm	R.P.H. Chang, Department of Materials Science & Engineering, Northwestern University. "Challenges in Teaching K-12 STEM"
2:40 pm-3:40 pm	Breakout sessions
4 pm-5 pm	Breakout session reports followed by open discussion Moderator: Larry Woolf; Scribe:Greta Marie Zenner

FRIDAY, SEPTEMBER 19, 2008

Session 3 MSE Education Strategies for the General Public
Session Chair: Greta Marie Zenner; Scribe: Larry Woolf

Goals: Discussions related to the need to and importance of introducing MSE principles and concepts to the general public

Anticipated Outcome: Strategies for communicating to the public and policy makers about materials science and engineering issues

8 am-8:30 am	Dietram Scheufele, Department of Life Sciences Communication, University of Wisconsin-Madison. "The Science of Effective Communication: Lessons for Public Outreach"
8:30 am-9 am	Shenda Baker, Department of Chemistry, Harvey Mudd College. "Connecting the Public with Materials Science—Sustainable Approaches"
9:10-10:10 am	Breakout Sessions
10:30-11:30 pm	Breakout session reports followed by open discussion Moderator: Larry Woolf; Scribe: Chandralekha Singh

Session 4 Graduate Education for the Materials Scientists and Engineers of the Future
Chair: Joe Whitehead; Scribe: Bob Hamers

Goals: Discussions related to the core of a modern MSE education at the doctoral level, especially across materials-designated and materials-related programs, how to provide effective interdisciplinary training to MSE students across various disciplines, and how to prepare them for the demands of globalization of MSE research and development

Anticipated Outcome: Strategies for improving MSE education for Ph.D. students across different departments

12:30 pm-1 pm	Wendy Cieslak, Sandia National Lab. "The Importance of Interinstitutional Collaboration for Graduate Education"
1 pm-1:30 pm	Susan Sinnott, Department of Materials Science and Engineering, University of Florida. "Engineering the Graduate Curriculum for the 21st Century"
3 pm-4 pm	Breakout session reports followed by open discussion Moderator: Bob Hamers; Scribe: Paul Russo
4 pm	Workshop adjourns

7. LIST OF PARTICIPANTS

Ivan Amato
C&E News, Managing Editor

David Bahr
Washington State University, Mechanical & Material Engineering

Gary Benenson
City College of New York, Chemistry

Kristin Black
Stanford University, Education Director, CPIMA

Gillian Bond
New Mexico Institute of Mining and Technology, Materials Department

Bruce Clemens
Stanford University, Professor, Materials Science & Engineering

Larry Dalton
University of Washington, Chemistry

Duane Dimos
Sandia National Laboratory; TMS, Director, Materials Science & Engineering

Arthur Eisenkraft
University of Massachusetts, Science Education

Paulo Ferreira
University of Texas, Mechanical Engineering

Jerry Floro
University of Virginia; Materials Research Society, Materials Science & Engineering

Stacy Gleixner
San Jose State University, Chemical & Materials Engineering

Rachel Goldman
University of Michigan, Materials Science & Engineering

Nancy Healy
Georgia Institute of Technology, Education Coordinator for NNIN

Ted Hodapp
American Physical Society, Director of Education & Diversity

Jim Hutchinson
University of Oregon, Organic, Organometallic & Materials Chemistry

Christine Keating
The Pennsylvania State University, Chemistry

Roger Kirby
University of Nebraska, Lincoln, Astronomy & Physics

David Lederman
West Virginia University, Physics

Richard LeSar
Iowa State University, Chair, Materials Science & Engineering

Subhash Mahajan
Arizona State University Director, School of Materials

Larry Malone
Lawrence Hall of Science, FOSS Co-Director

Eric Marshall
NY Hall of Science, VP Strategic Partnerships & Innovation of TryScience.org

Laurie McNeil
University of North Carolina- Chapel Hill, Physics & Materials Science

Patricia Mead
Norfolk State University, Professor of Engineering, School of Science and Technology

Amy Moll
Boise State University, Engineering

Michael Moloney
National Research Council of the National Academies, Associate Director, National Materials Advisory Board

Sarah Morgan
University of Southern Mississippi, Professor, School of Polymers & High Performance Materials

Christine Morrow
University of Colorado-Boulder, Director of Education & Science Discovery educator

Cathy Murphy
University of South Carolina, Chemistry

Adam Powell
Opennovation, Engineering Consultant, Materials Scientist, Principal of Opennovation

Ashley Predith
Proceedings Writer/Editor

Ainissa Ramirez
Yale University, Engineering

Ryan Roeder
University of Notre Dame, Aerospace & Mechanical Engineering

Pamela Rosenstein
WGBH Boston, Development Producer, NOVA

Paul Russo
Louisiana State University, Macromolecular

Lyle Schwartz
ASM Materials Education Foundation, Senior Research Associate, Materials Science & Engineering

Ram Sheshadri
University of California-Santa Barbara, Professor, Materials

Winston Soboyejo
Princeton University, Mechanical & Aerospace Engineering

Daniel Steinberg
Princeton University, Outreach Director for PCCM

Bob Tinker
Concord Consortium, President & CEO

John Venables
Arizona State University, Physics

KEYNOTE SPEAKERS

Diran Apelian
Worcester Polytechnic Institute; President TMS, Director of Metal Processing Institute; Mechanical Engineering

Shenda Baker
Harvey Mudd College, Chemistry

Bob Chang
Northwestern University, Materials Science & Engineering

Wendy Cieslak
Sandia National Laboratory

Cherry Murray
Lawrence Livermore National Laboratory, Principal Associate Director for Science & Technology

Kevin Jones
University of Florida, Chair, Materials Science & Engineering

Phil Sadler
Harvard University, Astronomy

Dietram Scheufele
Department of Life Sciences Communication at University of Wisconsin and Center for Nanotechnology in Society at Arizona State University

Susan Sinnott
University of Florida, Materials Science & Engineering

STEERING & ORGANIZING COMMITTEE MEMBERS

Laura Bartolo
Kent State University, Professor, Materials Informatics Lab

Warren E. Collins
Fisk University, Director, CPCoM Research Center, Physics

Robert Hamers
University of Wisconsin, Chemistry Department Chair, Materials Chemistry Professor

Ian Robertson
University of Illinois, Urbana-Champaign, Materials Science & Engineering Department Chair, Professor of Materials Science & Engineering

Chandralekha Singh
University of Pittsburgh, Physics & Astronomy Professor

Rob Thorne
Cornell University, Physics Professor

Joe Whitehead
University of Southern Mississippi, Professor & Dean, College of Science & Technology

Larry Woolf
General Atomics, Principle Optical Scientist/Program Manager

Greta Marie Zenner
University of Wisconsin, Engineering Physics

Susan Zernicke
University of Wisconsin, Division Coordinator

8. DISCUSSION QUESTIONS AND SUGGESTED READINGS

Suggested Reading for All Sessions

- http://www.cwsei.ubc.ca/Files/Wieman_talk_Mar2008.pdf
- http://www.cwsei.ubc.ca/about/BCCampus2020_Wieman_think_piece.pdf
- Rationale for the development of K-12 National Science Education Standards: http://www.nap.edu/openbook.php?record_id=4962&page=12
- An example of Learning Goals at UBS and CU: http://www.cwsei.ubc.ca/resources/files/Learning_Goals_at_UBC%20and_CU_examples.pdf
- Another useful resource is at least the executive summary of College Learning for the New Global Century: www.aacu.org/advocacy/leap/documents/GlobalCentury_final.pdf

Discussion Questions for the Public Education and Outreach Session

1. What do they know? What do we think general, non-expert audiences know about materials science and engineering (MSE)? How do we collect that information? If people do know something about MSE, how have they learned that information and from what source(s) did they get it? What do we see as the major gaps or misconceptions in what they know?
2. What do we believe they should know? What should be our goals for sharing MSE with the different segments of the non-expert general audience? How can we, as a community, come to a consensus as to what these goals should be? What should be the goals in terms of cultivating MSE understanding, awareness (including careers), enthusiasm?
3. How can we promote learning using the media? What kinds of media (TV, Internet, social networking, magazines, newspapers, popular science books, etc.) should the MSE community consider for sharing MSE with a broader community? Why? What is our current understanding of what currently exists and what should be developed? How do we as community come to a consensus to determine what exists and what should be developed? What kinds of media and formats would serve specific populations most effectively and how do we determine this? How can we as a community work with members of the media to make MSE more engaging, interesting, and relevant for non-expert audiences? How can we improve the MSE education, awareness (including careers), and enthusiasm of general non-expert audiences using the media?
4. How can we promote learning using informal science education? What kinds of museum (physical and web based) exhibits and/or programs have been developed? How effective have they been? How has their effectiveness been determined and how can their effectiveness be improved? What kinds of exhibits and/or programs should be developed? How do we determine those that will have the most impact? What kind of impact -education, awareness (including careers), enthusiasm -is desired? How can we as a community work with the informal science education community to make MSE engaging, interesting, and relevant for non-expert audiences? How can we improve the MSE education, awareness (including careers), and enthusiasm of general non-expert audiences using informal science education?

Suggested Readings for the Public Education and Outreach Session

- "The Public and Nanotechnology: How Citizens Make Sense of Emerging Technologies," Dietram A. Scheufele and Bruce V. Lewenstein, *Journal of Nanoparticle Research* (2005), vol. 7, pp. 659-667.
- "Engaging the Scientific Community with the Public," Rick Borchelt and Kathy Hudson, www.scienceprogress.org, April 21, 2008
- Scientists in Science Education: http://www.bscs.org/pdf/bscssise08.pdf
- The NSF Informal Science Education Program: http://www.nsf.gov/pubs/2008/nsf08547/nsf08547.htm
- Public attitudes about science/engineering: http://www.nsf.gov/statistics/seind08/c7/c7h.htm
- *Raising Public Awareness of Engineering*: http://www.nap.edu/nap-cgi/execsumm.cgi?record_id=10573
- How well informed is the public about engineering: http://www.nap.edu/openbook.php?record_id=10573&page=15

Discussion Questions for the Kindergarten Through 12th Grade (K-12) Education Session

1. Materials Education Standards: Determine if there is a need to define core material concepts for K12 and how that should be best accomplished. Should there be grade level standards? Or should there just be one set of standards for what students should know and be able to do by the time they graduate from high school? Or should there be no standards? Can these concepts be presented so that they form a cohesive learning progression through K-12? If needed, how should these standards be developed?
2. How to incorporate Materials Education curricula in K-12: Determine if we need to introduce materials science and engineering into the K-12 system, and if so, how that can be best accomplished. Should there be separate instructional modules that can replace topics typically covered in high school? What types of instructional materials, including assessments, are needed to improve materials education at the K-12 level? What instructional materials currently exist for K-12? What needs to be developed for K-12? Should there be textbooks that include chapters on materials education? How can all this be accomplished? Is this feasible in a curriculum dominated by existing standards, No Child Left Behind, and associated high stakes testing?
3. Professional development of K-12 teachers: What types of professional development of teachers are needed to improve materials education at the K-12 level? Who can provide this instruction? How can pre-service instruction be done? How can in-service instruction be done? Who can perform the professional development? Do instructional materials need to be developed for professional development of K-12 teachers in materials education? How can teachers be best instructed to learn both the curriculum, content specific pedagogy (if it exists), and assessment?
4. Increase student interest in materials careers: Determine how to assess and then increase student interest in and knowledge about post-high school and career opportunities in materials science and engineering. What do students know about materials science as a potential major in college? How can we increase their ability to learn about college majors? What do students know about materials science as a career? How can we increase their ability to learn about careers, including real-life examples of career paths, what materials scientists and engineers do, and typical pay scales for given education levels and years of experience? Should booklets be prepared about this career? Should we encourage the writing of popular books for K-12 about materials scientists and their contributions to society as a means to increase student interest?

Suggested Reading for the Kindergarten Through 12th Grade (K-12) Education Session

- Sections dealing with science content standards: http://www.nap.edu/html/nses/6a.html
- Professional development: http://www.nap.edu/html/nses/4.html
- For the K-12 education sessions, see the following newsletter, as it summarizes the state of the art science and physics education for K-12: http://www.aps.org/units/fed/newsletters/summer2007/index.html (all the articles except for the Teacher Preparation Section)
- Another useful article on enhancing science teaching and student learning could be useful to think about how to apply the lessons learned from K-12 curriculum development to undergraduate and graduate education: http://www.bscs.org/pdf/presentation-perspectiveaug06.pdf
- K-12 participants should also be aware of the Materials World Modules: http://www.materialsworldmodules.org/
- The ASM Materials Education Foundation provides many programs for K-12 students and teachers, including materials camps: http://asmcommunity.asminternational.org/portal/site/www/Foundation/ http://asmcommunity.asminternational.org/portal/site/www/Foundation/Students/Camps/
- The following articles are also useful background reading for curriculum and professional development:
    - "Engineering Competitions in the Middle School Classrooms: Key Elements in Developing Effective Design Challenges," P. M. Salder, H. P. Coyle and M. Schwartz.
    - "Unraveling a Knotty Design Challenge: PD for Engineering K-12," Gary Benenson & James L. Neujahr (Analysis and Design of Shopping Bags) http://citytechnology.ccny.cuny.edu/Design_Packaging.html
    - Testing and Analysis of tape: http://citytechnology.ccny.cuny.edu/Design_Fixing1.html
    - The Sadler et.al., Benenson and Neuhajr articles are available at: http://www.chem.wisc.edu/2008_nsf_workshop/schedule.html
    - *Benchmarks for Science Literacy: Materials and Manufacturing*: http://www.project2061.org/publications/bsl/online/index.php?chapter=8#B0

Discussion Questions for the Undergraduate Education Session

1. Should materials science and engineering move towards a professional MSc degree as the entry level degree into the profession? What are the pros and cons of such a move?
2. What is the importance of "soft' versus "hard" skills in the education of materials scientists and engineers? This question should be considered in terms of the impact of globalization of materials science and engineering and the workforce in general.
3. Should materials science and engineering embark on major revolution of its core curriculum? Can both traditional (e.g. corrosion, phase diagrams, etc.) and modern (biology, computational materials science, cyber-enabled discovery) topics be taught at an appropriate level within the constraints of limited credit hours? Are undergraduate research experiences important to the development of materials scientists and engineers?
4. How can the gulf between materials science and engineering designated and related programs be bridged? Given the proliferation of materials science courses in related departments, is there a need for designated materials science and engineering program?

Suggested Reading for the Undergraduate Education Session

- ABET requirements for materials science and engineering and related departments: http://www.abet.org/Linked%20Documents-UPDATE/Criteria%20and%20PP/E001%2008-09%20EAC%20Criteria%2012-04-07.pdf
- *Educating the Engineer of 2020* and related publications: http://www.nap.edu/catalog.php?record_id=11338

- *The Engineer of 2020: Visions of Engineering in the New Century* (Paperback) http://www.amazon.com/Engineer-2020-Visions-Engineering-Century/dp/0309091624
- *The 21st-Century Engineer: A Proposal for Engineering Education Reform* by Patricia D., Ph.D. Galloway (Paperback-Nov 1, 2007)
- Undergraduate Research Hunter, A., Laursen, S., & Seymour, E. (2006). Becoming a scientist: The role of undergraduate research in students' cognitive, personal, and professional development. *Science Education*, 91(1), 36-74. Available at: amath.colorado.edu/uploads/event_docs/BECOMING%20A%20SCIENTIST%20Hunter%20Laursen%20and%20Seymour.pdf
- Seymour, E., Hunter, A.-B.,Laursen, S.L.,& DeAntoni,T. (2004).Establishing the benefits of research experiences for undergraduates in the sciences: First findings from a three-year study. Science Education, 88(4), 493 - 534. Available at: amath.colorado.edu/uploads/event_docs/ESTABLISHING%20THE%20BENEFITS%20OF%20UR%20Seymour%20Hunter%20Laursen%20DeAntoni.pdf
- *Computational Materials Engineering: Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security*. http://www.nap.edu/catalog.php?record_id=12199

Discussion Questions for the Graduate Education Session

Course Curriculum

1. Is there (or should there be) a core set of courses for modern materials science and materials engineering education at the doctoral level, especially across materials-designated and materials-related programs?
2. If so, can we define it? Will it be different for materials science vs. materials engineering?
3. If it is different for different science and engineering departments, why so?
4. Is it desirable that common courses in materials science and engineering be taught to graduate students in different departments; and if so, is it feasible with different departments being territorial?
5. Who is in a position to convey and implement these changes related to core curricula in different departments and how can we give incentive to different departments to consider a common core and joint courses?
6. How can we overcome the barriers to working together on these issues and look at similarities rather than differences?
7. The answer to the above questions depends upon the goals of the Ph.D. training in materials science and engineering in different departments, so it will be useful to discuss how they are the same or different in different departments.

Interdisciplinary Training

1. What are ways to incorporate interdisciplinary training into the academic infrastructure of materials science and engineering graduate education?
2. What are the major barriers to incorporating interdisciplinary training into the academic infrastructure of materials science and engineering graduate education? What are the key components necessary for its success?
3. How can we provide interdisciplinary training to graduate students in different departments doing research in materials area so that they can benefit from what other graduate students are doing?
4. Is the goal of the NSF IGERT program on target with what is truly required for interdisciplinary training of graduate students in materials science and engineering programs? If not, why?
5. What have materials research based IGERTs accomplished from an interdisciplinary training perspective? What have they not accomplished?
6. Who are the key people in an academic organization to facilitate the incorporation of interdisciplinary training into materials science and engineering education? Would the

initiative have a higher chance of success if it were grassroots effort initiated by interested faculty member from different departments working together?

7. What are possible incentives to encourage departments participate in the interdisciplinary training of students?
8. Should Ph.D. students be encouraged to choose advisors outside of the discipline and thus, the department housing their degree program?

Career Preparation

1. What is innovation and how important is innovation in graduate education in materials science and engineering?
2. How can graduate students be helped to become innovative? How can they be helped to see the "big picture"?
3. What fraction of future jobs for graduate students in materials science and engineering will require a high level of innovation?
4. How important is it to expose graduate students to the entrepreneurial aspect of research?
5. Is the exposure to the entrepreneurial aspect of research equally important for graduate students in science and engineering departments?
6. What fraction of jobs for graduate students in materials science and engineering are entrepreneurial in nature?
7. Is the number of jobs that are entrepreneurial in nature likely to increase significantly?
8. Is there sufficient time during a Ph.D. program to expose students to entrepreneurial aspect of research?
9. Who are the key people in an academic organization to facilitate the incorporation of interdisciplinary training into materials science and engineering education? Would the initiative have a higher chance of success if it were grassroots effort initiated by interested faculty member from different departments working together?
10. What is the role of globalization on materials education in general and entrepreneurial aspect of research in particular?
11. Does globalization affect materials science vs. materials engineering in similar manner or differently? Why?

Information Technology

1. What role does alternative education, such as the internet and digital libraries, play in materials education at the graduate level?
2. Are we fully exploiting these resources for graduate education and, if not, why has the progress been slow? How can these resources be exploited fully?
3. How can we encourage and inform graduate students and their advisors about these resources?
4. What are effective strategies for improving the existing resources available?

Suggested Reading for the Graduate Education Session

» *Reshaping the Graduate Education of Scientists and Engineers*. This report was an outgrowth of the 1993 Committee on Science, Engineering, and Public Policy (COSEPUP) report, Science, Technology, and the Federal Government: Nationals Goals for a New Era. *Reshaping the Graduate Education of Scientists and Engineers* analyzes the preparation of Ph.D. scientists and engineers by the U.S. system of graduate education in light of a global economy that is more competitive technologically and limited research support within the U.S. The report was published in 1995. Weblink: http://search.nap.edu/readingroom/books/grad/

» *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*. The report by the Committee on Prospering in the Global Economy of the 21st Century was created by the National Academies as the result of a Congressional request from Senators Lamar Alexander and Jeff Bingaman to identify strategies to enhance U.S. competitiveness and security in the global community of the 21st century. The committee recommended that policymakers 1) increase America's talent pool by improving K-12 mathematics and science education; 2) sustain and strengthen America's commitment to long-term basic research; 3) develop, recruit, and retain high achieving domestic and foreign students, scientists, and engineers; and 4) ensure that the United States is the premier place in the world for innovation. The report was published in 2007. Weblink: http://www.nap.edu/catalog.php?record_id=11463

- *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*. The project provides a set of recommendations to guide engineering educators, employers, professional societies, and government agencies in modifying engineering education to produce the "Engineer of 2020" as defined by the initial phase of this project. The "Engineer of 2020" is a vision or visions of engineering in the 21st century based on rapidly evolving technology, national security, infrastructural needs in advanced countries, environmental challenges, and the interdisciplinary nature of current and future science and engineering. The report was produced by the Committee on Engineering Education, National Academy of Engineering and was published in 2005. Weblink: http://www.nap.edu/openbook.php?isbn=0309096499
- *A Decade of Action: Sustaining Global Competitiveness*. The Biological Sciences Curriculum Study (BSCS) organized a panel review of recommendations from 20 reports published by business and industry groups, government agencies, and professional organizations. The review resulted in generalized suggestions for modification of science, technology, engineering, and mathematics (STEM) education with a focus on K-12 education that would produce a 21st-century workforce and position U.S. competitiveness in the global economy. Published in 2007, the project was supported by the Office of Science Education, National Institutes of Health. Weblink: http://www.bscs.org/news/pages/decadeofaction.html
- Reenvisioning the Ph.D. The project, led by Jody D. Nyquist, was funded by the Pew Charitable Trusts and housed at the University of Washington. The project performed an "environmental scan" to identify programs, practices, and new visions of doctoral education that addresses the question: "How can we re-envision the Ph.D. to meet the needs of the society of the 21st century?" The website is periodically updated even though the project officially ended in 2003. Weblink: http://www.grad.washington.edu/envision/
- *Association of American Universities Committee on Graduate Education Report and Recommendations*. The committee analyzed the doctoral education process of its member institutions, and sought to identify best practices and associated guidelines that would allow the U.S. to continue its global leadership in doctoral education. Common criticisms of doctoral education in the U.S. include an overproduction of Ph.D. recipients, narrow training of doctoral students, and the practice of putting institutional needs ahead of student needs. The 1998 report addressed such issues as recruitment and admission, financial support, curriculum, and mentoring of graduate students. In addition, policy issues and program assessment were addressed. Weblink: http://www.aau.edu/reports/GradEdRpt.html