The Ecosystem of Research, Education, and Community

LYNNETTE D. MADSEN

Insights from research discoveries trigger innovation and invention, and ultimately lead to commercialization of new products. This influx of new technologies feeds the economy, and in turn also sparks interest in the community. It is this excitement and promise that attracts students to the field—our future workforce of policy makers, manufacturing experts, engineers, scientists, educators, and other leaders. Appreciation of the interdependence of these three cornerstones—research, education, and society—is essential in creating our best future.

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I. INTRODUCTION

HEREIN, the ecosystem of research, education, and community are described—both the interplay between them and their interdependence. I use university professors as the central actors throughout, and certainly they are key to research in academia, but it is my hope that others will identify with several aspects. I begin with the premise that there are three key aspects to be an outstanding professor and citizen—community, education, and research—paying attention to these cornerstones is important because they are also the levers in which we impact society. All three matter. With only research, you have discovery, perhaps even innovation, but no translation to the real world—the work is viewed as academic disengagement that is out of touch, *i.e.*, isolated within an ivory tower.[1] With only education, you teach established interpretations and motivate future generations to create but fail to contribute to scholarship directly. Would either of these be enough? Sure, but more is possible! The last key, community, seems to be the one most often overlooked. Community may be defined as the public, industry, parents and their children—families, government, scientists, engineers, and non-scientists. They say it takes a village—and indeed, these villages also have policy makers, manufacturing experts, engineers, scientists, educators, and other leaders. Professors live within the village and mold

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members of the village. To reap the full richness of opportunities, it is essential for professors to contribute to all three cornerstones by conducting original research, delivering enriching education to develop talent of a diverse population, and connecting and contributing to the communities in which they live.

II. EDUCATION

On a global basis, statistics show a lack of education above a mean of 12 years of schooling for 157 of the 189 countries surveyed by the United Nations[2] and a wide range of discrepancies (Figure 1).[3] So, only 42 nations have half or more of their youth graduating from secondary (high) school. Consequently, the number of students prepared to go forward with tertiary or university education is limited. In terms of university education, there are three aspects to consider—what is taught, how it is taught, and who is taught.

A. *Education Content*

In 2009, the National Academies of Engineering (NAE) endorsed the Grand Challenges Scholars Program (GCSP) and in doing so defined the value of engineering in a world context. Five competencies are identified for this undergraduate student engineering degree program framework:

1. Talent: being mentored on a research/creative experience that addresses a grand challenge,
2. Multidisciplinary: understanding engineering systems solutions that draw upon knowledge from different disciplines as developed through personal engagement,
3. Viable business/entrepreneurship: understanding, usually though experience, the necessity of a viable business model,
4. Multicultural: understanding different cultures, preferably through direct experiences, to ensure acceptance of proposed engineering solutions, and
5. Social consciousness: understanding that engineering solutions should serve society.

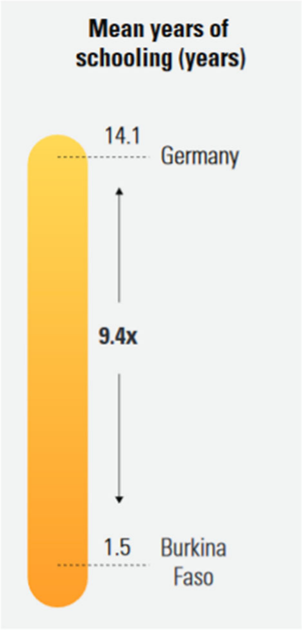

Fig. 1—Mean years of schooling (years). From Human Development Report Office, United Nations Development Programme, hdr.undp.org, reprinted under the Creative Commons Attribution 3.0 IGO license.

Fourteen grand challenges were defined by NAE (Figure 2). More than 100 engineering schools in twelve countries (Australia, Brazil, Canada, China, India, Italy, Malaysia, Romania, Singapore, Taiwan, the United Arab Emirates, and the United States) have implemented this program or are in the process of doing so.

B. *Education Delivery*

The days of a professor writing on a board, relaying the information contained in the course text, are over (or they should be). A recent, 2018, study analyzed science, technology, engineering and mathematics (STEM) teaching practices in U.S. and Canadian universities through classroom observations of 500^+ professors across 25 institutions.[4] The findings "imparted a lesson that might resonate with many students who sat through them: *Enough with the lectures, already*."[5] So much has progressed and transpired over the past 50^+ years from problem-based learning in 1969 at McMaster University, to MIT making course materials freely available in 2001, to machine learning today. It is anticipated that educational technology tools will adopt machine learning such that applications can appropriately group students, allocate resources, build lesson plans, grade examinations, and more. Key education developments and reports are listed on NSF's Cross-Cutting website within the Division for Materials Research.[6] It is no small feat to translate these developments into today's classrooms, laboratories, and other learning spaces. The University Materials Council (UMC), comprised of leaders from academic U.S., Canadian, and Australian university programs in the materials field, has been helping to accelerate this process.[7] It is necessary to explore advances in pedagogy, effective learning principles, and educational content delivery. Examining how to add active learning and entrepreneurship, and identification of best practices in providing innovative and inclusive teaching methods and tools is also needed. Of increasing importance are online learning modules and the incorporation of computational simulation tools into learning.

C. *Students of Today are Tomorrow's Workforce*

Everyone with talent and interest in science, technology, engineering, and mathematics (STEM) should be encouraged, advised, educated, trained, and mentored

Fig. 2—Grand challenges for engineering. Image used with permission of the National Academy of Engineering Grand Challenges for Engineering.

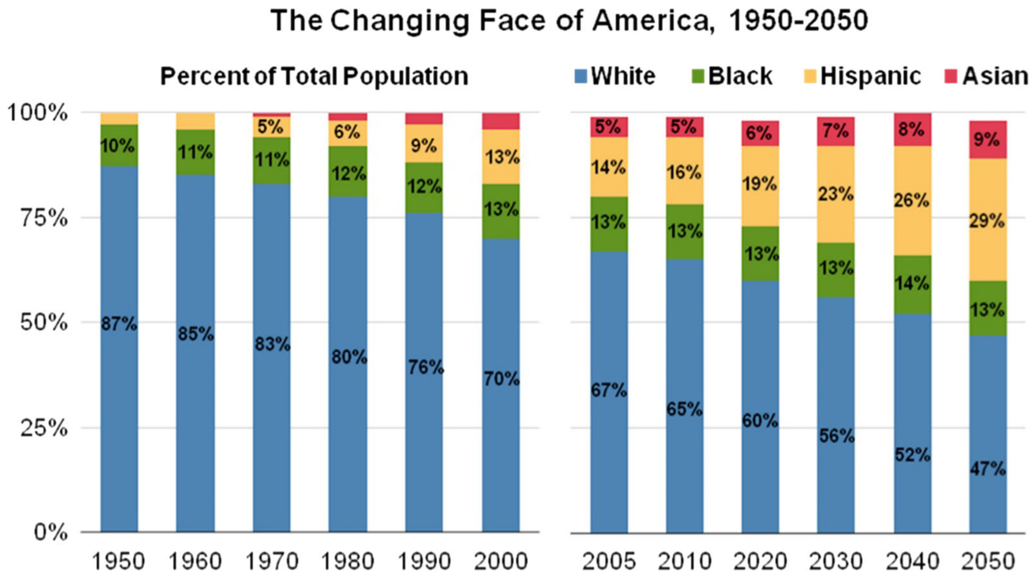

Fig. 3—The changing face of America, 1950 to 2050. Data from the Pew Research Center Population Projections.

towards such a career. Some, no doubt, will find other pathways, but may along their way may still develop science literacy. Ultimately, there is no place for elitism, or money being part of a pre-selection or screening process. The U.S. government stated in 2016, that "To meet the projected workforce need of 1 million additional STEM graduates by 2022, and to realize the vision of a highly diverse, creative, and sufficient STEM workforce and a STEM-literate citizenry, the Nation must engage all students."[8] The U.S. has reason to be concerned if the projected demographic changes occur (Figure 3). This figure shows both history and projection going forward several decades. If the demographic predictions hold, then the Asian population (shown in red) will go up 50 pct and increase from 6 to 9 pct, the Hispanic population (in yellow) will nearly double to 29 pct (*i.e.,* represent nearly one-third of the U.S. population), African Americans (in green) will remain steady at ~ 13 pct, and Whites (shown in blue) will shrink significantly going from 60 pct of the population to 47 pct, falling to below half of the U.S. population.

At present, there are significant education inequalities across different groups based on race, ethnicity, sex, and ability. This issue extends to other countries as indigenous groups are often not well represented among the highly educated, and women are well below par in many STEM fields. Recent studies have also indicated a reluctance by U.S. faculty to mentor female students to the same extent as male students.[9]

It is important that we educate and develop a diverse set of critical thinkers. Moreover, diversity in terms of team composition has been shown to have a positive impact in terms of solving complex problems.[10] Publications from diverse research teams receive significantly more citations and gender-diverse groups are noted to have higher quality results.[11]

III. TRAINING THROUGH RESEARCH

A dictionary definition of research is ''the systematic investigation into and study of materials and sources in order to establish facts and reach new conclusions.''[12] In introducing students (at any level) to research, they begin to understand the exploratory-hypothesis nature of research and how it progresses and converges on the truth. It is equally important for students that do not pursue a research career, to understand the process—the debate and on-going discoveries that guides the way to truth. This is one of several reasons why it is important to examine best practices in Materials Science and Engineering (MSE) undergraduate education as enrollments rise.[13] The objectives of a 2019 workshop were to discuss current trends, make projections, and establish best practices. The key directives from this workshop included (a) recruit diverse students and ensure high degree completion rates, (b) restructure course programming to facilitate a greater number of students to meet demands of employers, (c) enhance student engagement through active learning experiences, and (d) incorporate professional skill development into existing courses. The goals are to establish effective means to educate and engage students in the field, provide meaningful experiential and/or research experiences, and train and prepare them for careers in MSE and related areas. While the U.S. has few politicians[14] and policy makers with science/engineering backgrounds, this has not always been the case in China. Furthermore, some universities, such as Dartmouth, are quite forthcoming in promoting a combined engineering-politics education.[15] A step towards this goal are Congressional Science and Engineering Fellowships in Washington, D.C.[16] These fellowships include one jointly sponsored by the Minerals, Metals & Materials Society (TMS) and Materials Research Society (MRS).[17]

IV. RESEARCH

Looking again to how research is defined, we see that it varies across dictionaries (Table I) (and usage), but common factors pertaining to scientific research are ''investigation'' and ''new.'' It follows then that the current knowledge, the background, must be sufficiently well understood to appreciate any new findings. Another salient element is the investigation, which is often carried out in a systematic and purposeful manner to uncover new discoveries more efficiently. Researchers, whether they be in industry, government, or academia, are very good at this. However, writing compelling proposals about their intended research ideas remains elusive for some.

A. *Research Integrity*

Equally important as the research is its integrity. While neither scientist nor engineer rank at the top of most trusted or respected profession, they are not far from it in sixth and seventh position (at least in Canada, Figure 4).[22] This standing in the community is important for many reasons—ability to attract students to the field, government support of funding, *etc*. At the very bottom are politicians. Research misconduct and detrimental research practices have other consequences, *e.g*., impairment of advances in knowledge, misplaced research dollars, collateral damage to innocent collaborators, inquiry and investigation expenses, and sometimes negative effects on informants and whistleblowers.[23] The National Institute of Health in the U.S. has paid attention to research integrity for some time.[24] The U.S. National Academies recently released a report, Fostering Integrity in Research,[23] and a study on the reproducibility and replicability in science is underway (with sponsorship by NSF).[25] Other countries, *e.g*., in Europe[26] and South Africa[27] are also paying attention to these topics.

V. ENTREPRENEURSHIP

While material scientists (including physicists and chemists) are primarily concerned with discovery, engineers work at various points towards product commercialization. It is a difficult path from discovery to commercialization which has resulted in the term 'valley of death.' There are several milestones along this path (Figure 5) each with its own technical challenges. For example, if scale-up is difficult or impossible, then the viability of a concept for commercial production may be low or nil. Many politicians agree that small businesses are the backbone of our economy (as John Oliver captures from more than 30 politicians in one of his skits).[28]

Yet, another obstacle for many entrepreneurs is obtaining funding. While there are several sources, *e.g*., government, industry, private foundations and/or other investors, each requires time and effort to secure. I will provide one example to assist with this process within the U.S. As part of the National Nanotechnology

Table I. Definitions of Research

The systematic investigation into and study of materials and sources in order to establish facts and reach new conclusions. (Oxford[18])

Studious inquiry or examination especially: investigation or experimentation aimed at the discovery and interpretation of facts, revision of accepted theories or laws in the light of new facts, or practical application of such new or revised theories or laws. (Mirriam Webster[19])

Diligent and systematic inquiry or investigation into a subject in order to discover or revise facts, theories, applications, *etc*. (Dictionary.com[20])

A detailed study of a subject in order to discover information or achieve a new understanding of it. (Cambridge[21])

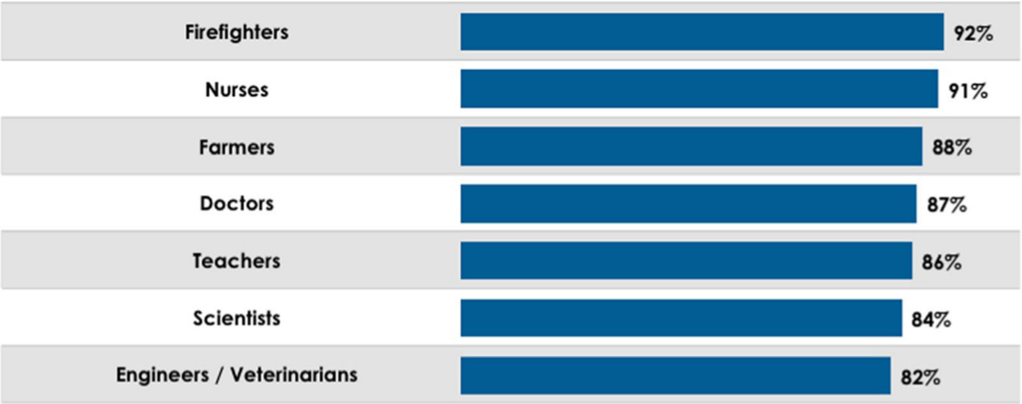

Fig. 4—Canada's most respected professions. 2018 Insights West Survey; used with permission.

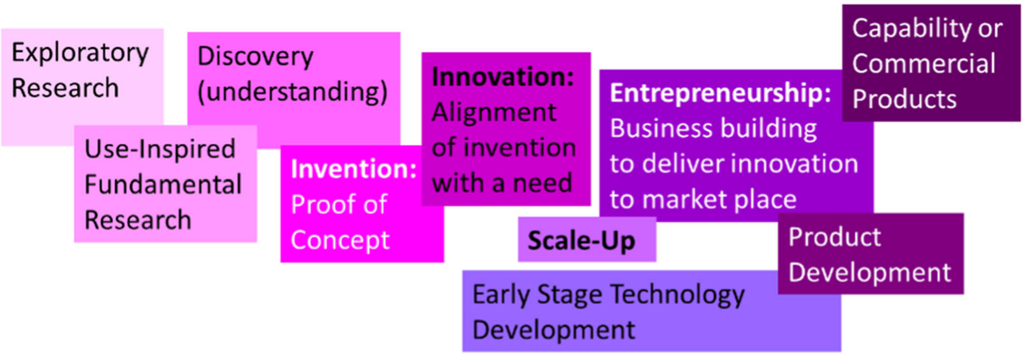

Fig. 5—The path from discovery to products has many milestones along the way.

Initiative, the National Nanotechnology Coordination Office (NNCO) worked with the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee to create a list describing more than 40 U.S. funding programs that foster commercialization of nanotechnologies.[29] Three categories are included: (i) Partnerships and Collaborations, (ii) Multi-Agency Funding Opportunities, and (iii) Specific Agency Opportunities. The latter category includes the Department of Defense (DOD), the Department of Energy (DOE), Department of Homeland Security (HS), Federal Aviation Administration (FAA), Intelligence Advanced Research Projects Activity (IARPA), The National Aeronautics and Space Administration (NASA), National Institute of Health (NIH), National Institute of Standards and Technology (NIST) and NSF.

The World Economic Forum publishes an annual Global Competitiveness Report.[30] Their Global Competiveness Index (GCI) captures and ranks the competiveness of 137 country's economies. They have identified twelve pillars that drive productivity and prosperity. Four are considered basic requirements: (i) institutions, (ii) infrastructure, (iii) macroeconomic environment, and (iv) health and primary education. Six are efficiency enhancers and they are (i) higher education and training, (ii) goods market efficiency, (iii)

Table II. Rank of Top Ten Countries in Terms of Global Competitiveness

1. Switzerland
2. United States
3. Singapore
4. Netherlands
5. Germany
6. Hong Kong SAR
7. Sweden
8. United Kingdom
9. Japan
10. Finland

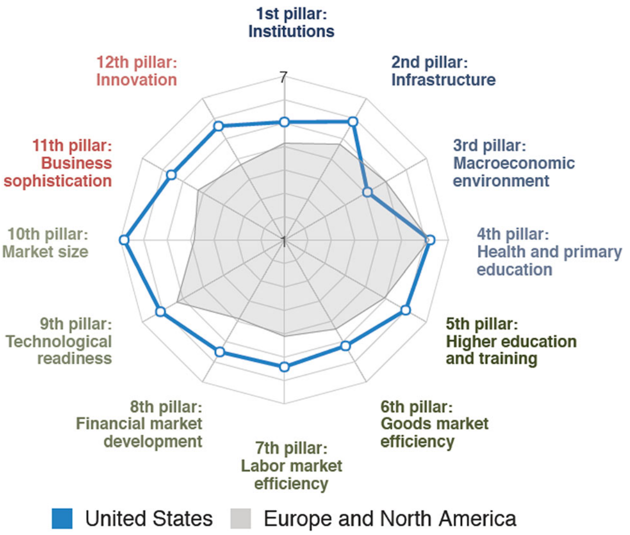

Fig. 6—Global Competitiveness Index 2017 to 2018 edition where 1 (center) signifies a weakness and 7 (perimeter) signifies a strength. Global Competitiveness Index 2017 to 2018 edition, World Economic Forum, Switzerland, 2017 to 2018 edition. Reprinted with permission.

labor market efficiency, (iv) financial market development, (v) technological readiness, and (vi) market size. The final two pillars—(i) business sophistication, and (ii) innovation—are labeled as innovation and sophistication factors. These interconnected pillars measure different aspects of a country's economic competitiveness. For the ninth consecutive year, Switzerland has topped this list (Table II). Across the board, the GCI identifies financial vulnerabilities as they affect competitiveness and ability to finance innovation and technological adoption as one of the main challenges for economic progress, public-private collaboration, and policy action.

The United States is ranked second (Figure 6). The U.S.' strong components are its performance in efficiency enhancers and innovation and sophistication factors, but it does not fare so well on the four basic requirements (where it is ranked 25th). In particular, the U.S.' macroeconomic environment, their worst pillar, is 83rd of the 137 countries included (and below the averages of both Europe and North America). A macro environment exists in the economy as a whole, and includes trends in gross domestic product (GDP), inflation, employment, spending, and monetary and fiscal policy. For example, fiscal deficits limit a government's ability to react to business cycles. In terms of the higher education and training pillar, the U.S. is third, behind Singapore in first position and Finland in second position.

VI. COMMUNITY

Beyond entrepreneurship, product development, and creation of small businesses, our communities have needs at the local level and on the global front. Mentioned already were the NAE grand challenges for engineering. With a broader perspective, the United Nations Educational, Scientific and Cultural Organization (UNESCO) has defined 17 sustainable development goals (Figure 7). Some of these are clearly overlapping (such as clean water and sanitation) with the NAE grand challenges.

Additionally, there have been many localized challenges (Table III). This small sampling includes a range of structural failures, collapses and other disasters; some causes are still unknown, or are due to a sequence of actions. The ship failures—Vasa and Titanic are history lessons now. The Tacoma Narrows Bridge and two Quebec Bridge failures are also behind us; the latter motivated licensure of professional engineers in Canada. Included are the two shuttle failures, and several examples of energy harvesting problems—St. Francis dam, Chernobyl, Centralia in Pennsylvania, and Deepwater Horizon. An environmental disaster arose from burning tires. Two examples of water pollution problems—Hamilton Harbour and Flint—are provided. And also, signs of poverty in several American inner cities are evident. Stronger or better materials may have prevented some of these disasters—but what is more interesting is that material researchers have the possibility to help provide solutions, particularly when they work with others. Two of these local challenges are discussed in more detail.

A. *Challenge 1: The Life Cycle of Materials*

The first challenge I will discuss took place in Hagersville, Ontario, Canada in 1990 (just after I started my Ph.D. studies in Materials Science). Hagersville is about 45 km away from McMaster University. A pile of 14 million tires was accumulated on an 11-acre storage site with the dream of recycling them. The province tagged it as a fire hazard and was already in the courts with the owner. Before the situation was resolved, the tires were intentionally set on fire by youths. The fire burned and then smoldered for 17 days (Figure 8). The toxic smoke drove 4000 people from their homes. At its peak, firefighters from 11 departments used 350 bottles of compressed air per day. To extinguish the fire, they employed four mechanical hoes, five bulldozers, a convoy of tanker

Fig. 7—Sustainable development goals. UNESCO and Sustainable Development Goals, © UNESCO, https://en.unesco.org/sdgs.

Table III. A Few Examples of Localized Challenges

Älvsnabben, Sweden	Vasa (1628 to 1961)	a Swedish warship, unstable and top-heavy with too much weight in the upper structure of the hull foundered early into its first voyage
St. Lawrence River, Quebec, Canada*	(1907 to 1908, 1916 to 1917)	Quebec Bridge, longest cantilevered bridge span in the world, collapses due to (i) a bent structural beam, (ii) an issue with the hoisting devices
North Atlantic Ocean	(1912)	Titanic, a British passenger liner, that sank after a collision with an iceberg dented the hull such that seams buckled and separated[31]
Hamilton Harbor, Hamilton, Ontario, Canada	(1917 to 1994)	pollution from dumping (sewage), industrial development, *etc.*
Los Angeles County, California, United States	(1928 to 1929)	catastrophic failure of the St. Francis dam
Tacoma, Washington, United States	(1940 to 1950)	Tacoma Narrows Bridge, a suspension bridge, collapsed due to aeroelastic flutter—a dynamic instability of an elastic structure
Centralia, Pennsylvania, United States	**(since 1962)**	**coal seam mine fire**
Kennedy Space Center, Merritt Island, Florida, United States	(1986 to 1988)	Space Shuttle Challenger (OV-99) broke apart due to failure of the O-ring seals which caused a breach in the solid rocket booster (SRB) at liftoff
Pripyat, Ukrainian SSR, Soviet Union	**(since 1986)**	**nuclear accident with uncontrolled reaction conditions at the Chernobyl power plant after safety system design failure**
Hagersville, Ontario, Canada	(1990 to 1991)	a fire at a tire recycling facility that burned for 17 days
Near Pacific Ocean	(2003 to 2006)	Space Shuttle Columbia disintegrated upon re-entering Earth's atmosphere likely due to a piece of foam insulation breaking off and causing damage to the thermal protection system
Gulf of Mexico	(2010 to 2014)	Deepwater Horizon, an offshore drilling rig, had an uncontrollable blowout caused an explosion on the rig
Flint, Michigan, United States	**(since 2014)**	**lead leached from pipes into residential drinking water**
Baltimore, Maryland, United States	**(since ~1970)**	**degraded infrastructure, deteriorated residential properties, homelessness, lack of public transportation, unemployment, violent crime, *etc.***

Bold entries continue to be problems today.
*The Quebec Bridge is particularly notable because it motivated licensure of professional engineers in Canada.

trucks, and two waterbombers. About 158,000 gallons of oil from the melted rubber were collected and processed at a nearby refinery. At a cost of more than C$10 million (for a year-long clean up), it is the worst environmental disaster in Ontario history. Since the time of fire, tire recycling fees are levied at the point of purchase, restrictions are placed on the size of tire piles, and an active recycling program is in place. Ninety-five percent of used tires are recycled into products, including landscaping tiles, rubber mats, landscaping mulch and rubberized surfaces for playgrounds and athletic facilities. So, the question is—what is the role of material scientists and engineers in terms of the lifecycle of commercial products and sustainability?

(a) (b) (c)

Fig. 8—Pile of 14 million tires on fire, February 1990, Hagersville, Ontario: (*a*) first night inferno: a silhouette in billowing flames during the early hours at the Tyre King recycling yard (credit: Paul Hourigan, Hamilton Spectator), (*b*) thick, black smoke rises from the Tyre King fire on the morning after the blaze was ignited (credit: Ted Brellisford, Hamilton Spectator) and (*c*) battle from the air (images reprinted with permission of The Hamilton Spectator).

B. *Challenge 2: Providing Basic Needs*

The second challenge concerns an inner American city and its degraded infrastructure, deteriorated residential properties, homelessness, lack of public transportation, unemployment, violent crime, and other on-going issues—I selected Baltimore as the example. A Brookings study considers Baltimore to be a typical American city.[32] The population represents the 30th largest metropolitan area in the country.[33] The poverty level for a family of four in 2018 is $25,100 per year.[34] Some regions of Baltimore have 40 pct of the population living below the poverty level.

Poverty and poor primary education are correlated. What responsibilities do the highly educated and well-off population have, and specifically how can materials scientists, engineers, and educators play a role? While those questions will not be completely answered, a few examples of partial solutions are provided.

1. *Education is a Basic Need*

In many cases, quality elementary or primary as well as secondary (high school) education is critical for further education and/or employment. Johns Hopkins University (JHU) has a few efforts targeting just this area—one example is SABES (STEM Achievement in Baltimore Elementary Schools) through a partnership with Baltimore City Public Schools (BCPS).[35] While this 6-year effort was initially funded through NSF, it is still on-going (for the time-being) and seeks to improve STEM curriculum and delivery, and to develop after school programs.

The UTeach Institute located at the University of Texas at Austin has the slogan ‘‘We prepare teachers. They change the world.’’ UTeach is a teacher preparation program with the goal of increasing the number of qualified STEM teachers in U.S. secondary schools. It has now partnered with 45 universities in 22 states. Included in this effort are Towson University (with Towson UTeach) and the University of Maryland at College Park (with Terrapin Teachers).

2. *Housing is a Basic Need*

In 2005, Utah set the goal of ending chronic homelessness. The chronically homeless include those with a ‘‘disabling condition’’ such as serious mental illness, an addiction, or a physical disability or illness. The idea underpinning Housing First is that housing comes first, services later. Residents pay some rent—either 30 percent of income or up to $50 a month, whichever is greater. It is also cost effective for Utah since the United States government (Department of Housing and Urban Development (HUD)) estimates that the annual cost of homelessness at $30,000 to $50,000 per person due to their use of services such as emergency room visits and jail time. Moreover, having a home makes holding down a job easier. Baltimore has examined turning their thousands of vacant houses into safe affordable homes through a Vacants to Value (V2V) initiative.[36]

3. *Employment is Essential*

Another effort in Baltimore, BLocal, has as its priority, building, hiring, and buying locally, particularly in engaging women- and minority-owned businesses.[37] This commitment has expanded to 27 partners and addresses opportunities from catering through to construction.

4. *Food and Water are Necessities*

The City of Baltimore Sustainability Commission is a 21-member body appointed by the Mayor which at this time includes a professor from a local university.[38] Additionally, they have five academic partners: JHU—Center for a Livable Future, Morgan State University, Penn State University, University of Michigan and University of Maryland, Baltimore County (UMBC). Previous efforts undertaken by Baltimore’s Sustainability Commission have been advanced or completed by residents, faith-based institutions, non-profits, city agencies, and businesses. Baltimore’s *Food Waste & Recovery Strategy* sets out to reduce the amount of food that is discarded, boost food donation, and expand community and commercial composting of food scraps. Similarly, efforts are made elsewhere in the world, *e.g.*, in France, a new law forbids food waste by supermarkets.[39] NSF and the U.S. Department of Agriculture National Institute of Food and Agriculture (USDA/NIFA) have partnered in a program called ‘‘Innovations at the Nexus of Food, Energy and Water Systems (INFEWS)’’ to support research that addresses the growing demand for food, energy, and water while also fostering sustainable ecosystems and training the next generation.

VII. COMMUNICATION WITH THE PUBLIC

While much focus is made on educating and engaging the next generation of STEM professionals, it is also important to educate the public—in particular, politicians, policy makers, leaders, and parents. It is imperative that we move beyond our immediate neighborhoods and ensure our reach includes underserved communities whether they are inner cities, suburbia, or rural regions. Cornell University (in Ithaca, New York, U.S.) boasts of its impact on every New York county on its front page.[40]

A. *Future Workforce*

A National Academies workshop addressed the development of a national STEM workforce strategy.[41] Identified factors of importance included defining what is meant by a "STEM-capable workforce" and who needs it, education and training pathways, understanding developments in education and their impact on STEM workforce readiness, identifying ways investments in education and training can enhance STEM workforce readiness, meeting employer needs, and I will add to their list, public appreciation of STEM careers. It is the latter that I will focus on. At the workshop, Rush Holt of the American Association for the Advancement of Science (AAAS) spoke about making science more appealing to the general U.S. population. Holt went on to state, "The lack of appreciation for the essential methods of science—that questions can be answered empirically and verifiably—means that every economic debate in the country, is based on ideology, not evidence, even though economics is in large part an empirical science, generating evidence an ordinary person should be able to evaluate and that all citizens should demand be the basis of any policy argument their elected officials make."[41] Freeman Hrabowski, from the UMBC, gave a keynote address at this workshop and stated, "it is clear the public does not understand the importance of STEM for the future of the nation's children. Correcting this perception problem will require a change in culture across the entire U.S. educational system, but in particular at the nation's colleges and universities."[41]

A fundamental motivation to educate the public—in particular parents, teachers, and children—is to have them better understand STEM occupations, aspire to join this sector of the workforce, and appreciate the education prerequisites. Generally, there is a poor understanding of what an engineer's or scientist's job entails; stereotypes exist for both. Additionally, the public is often hard-pressed to distinguish the roles of scientists from engineers, and vice versa. It can be difficult to attract students to STEM fields for a myriad of reasons.

(1) Young girls may not envision themselves in such a role. The modern standard image of a scientist is predominately a laboratory scientist.[42] David Chambers set out to determine at what age children first develop distinctive images of scientists. His work was conducted over a period of 11 years (1966 to 1977) through the Draw-a-Scientist Test (DAST) administered to 4807 children. Seven types of indicators were chosen, *e.g.*, lab coat (often white), eyeglasses, *etc*. Twenty-eight women scientists were drawn; only girls drew women scientists. Building on these results, a 2007 study found girls were more likely than boys to draw female scientists, and half of the girls drew a female scientist.[43] Children cited television as the primary inspiration for their scientist drawings. Dana Scully, a character on the American science fiction drama television series, The X-Files, is considered by many women to be a strong and intelligent role model.[44] Additionally, there are race and ethnicity stereotypes as well as implicit bias working against the success of underrepresented groups. It can be difficult for individuals to recognize some of the bias, discrimination, or harassment and to understand their options for dealing with it.

(2) Students may not appreciate that careers exist at all levels (Figure 9). For example, they may not know how careers as technologists or technicians differ from careers as an engineer—and the different education requirements for each.

(3) It is problematic for teenagers to make informed decisions about selecting a university or college (in addition to a major field of study). There are too many ways that academic institutions are presented today on the web, thereby making it difficult to appreciate what rankings or factors are relevant. Teenagers often do not have the maturity to fully appreciate how to rank their preferences (or options) and reach the best compromise. Underrepresented group members may select an academic institution based on their

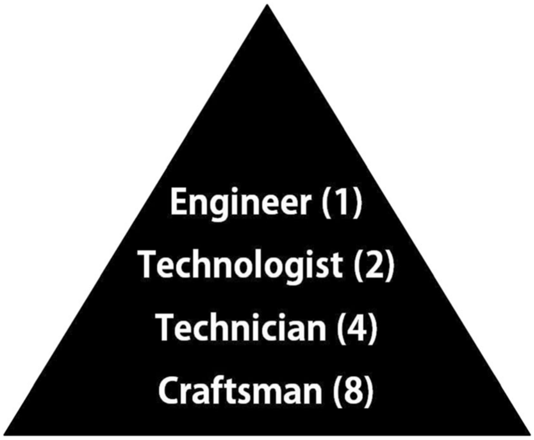

Fig. 9—Pyramidal hierarchy of technical roles—for each engineer, there are 2 technologists, 4 technicians and 8 craftsmen. Used with permission of Author, Okwuagbala Uzochukwu Mike P, of "The Engineering Family or Team: Who are They" found at https://hubpages.com/technology/The-Engineering-Family-or-Team-Who-are-They).

perception of their own intelligence or fit to their group and in doing so may select a less prestigious institution. Students may not understand why or how to move to a more competitive institution based on their talents.

(4) Students may be poorly prepared for university due to insufficient education at the secondary level, lack of study habits, or failure to have selected the right prerequisite courses.

B. *Science Literacy*

Another strong motivator to communicate with the public is to improve science literacy. There are three aspects to this: the scientific method, motivations for research, and knowledge.

1. *Appreciating the Scientific Method*

There is a scientific method (a way of thinking through problems or hypotheses). By understanding the scientific method and approaches, *i.e.,* how discoveries are made, the push to develop a deeper understanding, and the convergence towards the complete truth, the public can better appreciate the validity of findings. There is a debate or argument that is often needed to arrive at the truth. This is also true in other fields such as medicine, diet, and health. For example, for many years it was believed that eating eggs that contain cholesterol would boost one's own cholesterol levels and accordingly, many people avoided eating eggs. Years later, we know this to be false. The public has difficulty in distinguishing what is well-established vs. what is being debated.

2. *Understanding Why and How Science is Conducted*

A non-scientist may wonder why basic fundamental science is not already known—if it is indeed so basic. They might also ask why fundamental science takes one to two decades to be implemented into an application, device or other product? Additionally, the question could be raised, is exploratory research really needed (if no immediate use is envisioned). Added to this, even scientists and engineers struggle to make the connections between discovery, innovation, commercialization, economic prosperity, and quality of life.

It is not immediately obvious why scientists should collaborate internationally given that countries compete on several fronts. More than a decade ago I published an article on the value of international collaborations.[45] Despite recent controversies, the rationale for collaboration holds. The reasons fall into three categories: (1) increased scientific capability, (ii) advantages of cooperation, sharing, and validation for scientific progress, and (iii) benefit for international relations and prosperity. I am reminded of a statement from John Dewey made in 1916, "It is not enough to teach the horrors of war and to avoid everything which would stimulate international jealousy and animosity. The emphasis must be put upon whatever binds people together in cooperative human pursuits and results, apart from geographical limitations." This too is applicable today. What does a flat world mean for science? How is science important for diplomacy? What does pre-competitive research mean and how might collaboration be beneficial for all parties involved?

There is little appreciation of modern engineering manufacturing environments and consequently the field fails to attract many students even though jobs in this sector can be highly paid and interesting. Technological evolution and advances can result in safer jobs and products, and entirely new positions and job functions. The advantages of automation (in terms of speed, accuracy, safety, *etc.*) are not always fully appreciated, particularly when they cause certain jobs to disappear.

3. *Science Literacy: Knowledge*

While knowledge of science and engineering is largely considered advantageous (for many of the reasons already espoused), this knowledge is sometimes interpreted through the lens of religion or politics.[46] Cognitive dissonance is created when there is a clash between beliefs deeply tied to one's identity and new information. Selective learning occurs where facts that confirm their worldview are more readily absorbed than facts that challenge it.[47] Additionally, motivated reasoning can be triggered to construct a biased argument that arrives at or endorses a preferred conclusion.[48] Consequently, for controversial topics (such as stem cell research and human evolution) more polarized beliefs arise from increased scientific education and literacy and these are correlated with both political and religious identity.[47] For other topics such as nanotechnology and genetically modified foods, this polarization was not found.[47]

VIII. SUMMARY

I have examined the ecosystem of research, education, and community by going full circle, stopping at pertinent points. Universities and their employees, including professors, are uniquely positioned to contribute to this ecosystem. A university's mission, vision, and strategic plan can focus efforts to address key aspects.

Having relevant and socially meaningful content in engineering degree programs is paramount to attracting a broad set of students. Development of talent regardless of differences (in race, ethnicity, sex, *etc.*) is called upon to have a highly diverse, creative, and sufficient STEM workforce. The NAE GCSP ties engineering degree programs to grand challenges, multidisciplinary education, and entrepreneurship in a multicultural and societally beneficial context. Teaching is no longer confined to lecturing while writing on boards in a classroom; a broader platform that enhances learning is called upon to create the next generation of critical thinkers.

Research explores and tests hypotheses in a systematic manner and guides us to the understanding of the truth. Science literacy of the public has several dimensions—appreciating the scientific method, understanding the motivations for science and engineering research, and embracing the knowledge attained. Students engaged in research come to more deeply appreciate the debate involved and corrections made based on findings along the way. Research integrity is critical for obtaining community acceptance of the results. Even then, preconceived notions and biases can interfere with this acceptance.

Moving from research to discoveries and translating the results into the public realm whether to tackle challenges for the public good or for economic prosperity is important. Identifying the milestones between exploratory research and products can aid R&D investigators in finding critical funding. Challenges exist along a continuum from the local to global level—while progress is often made, some of these challenges remain unsolved and interfere with the quality of life. University engagement in these complex, and sometimes wicked, problems is paramount to shed the ivory tower image and bridge the gaps between academia and the public. Programs at universities such as service learning, study abroad, internships, engagement with local schools and humanitarian efforts can improve perceptions, foster better relations, and create pathways of cooperation.

The lack of understanding of STEM careers, poor preparation at the secondary level, and stereotypes impede the full participation of talented students. Lack of appreciation of the financial options and trade-offs can serve as another hurdle. Additionally, underserved populations often face additional barriers, including implicit and explicit bias; discrimination; harassment; inequity in terms of salary; unequal access to funding and resources; higher teaching and advising loads; and fewer speaking invitations.[48] Many teenagers and parents are unable to make informed decisions about the selection of a major and university at the outset and or even later on, if, *e.g.*, a transfer is called for.

It is reassuring to see university policies evolving to meet changing needs. Also, it is encouraging to see how policy and regulations might in some cases improve research integrity, since research findings and their evolution into products is such a key factor in society's economic advancement. I urge everyone to own this ecosystem of research, education, and community and to contribute, where they can, to its successful functioning; the world will be better for it.

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DISCLAIMER

To illustrate my points, I use examples from universities—it should not be inferred that these are the best or most important universities; I simply wanted real examples. I have given them credit (as I should, and as they deserve), but in no way I am promoting one university over another. Moreover, any opinion, findings, and conclusions or recommendations expressed today are mine and do not reflect the views of NSF.

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