Engineering 6 (2020) 728–732

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Views & Comments

Engineering in the 21st century: The Grand Challenges and the Grand Challenges Scholars Program

C.D. Mote Jr.

Regents Professor, University of Maryland, USA; Past President, US National Academy of Engineering, USA

Prologue

Engineering's fundamental mission to "create for users" has served humanity, prehistoric humanity, and other life forms, such as insects, fish, birds, and mammals, unwaveringly for hundreds to millions of years. What distinguishes human engineering from the engineering of other life forms is the singular human capacity to envision a "creation for users," then to create it and ultimately to implement it fulfilling an important "user need." Other life forms pass down engineering creations likely learned from their predecessors through an evolutionary process, like creating anthills, beehives, and bird nests. Their creations are learned replications of earlier experiences more than an intellectual response to new opportunities. User advancements without opening new frontiers limit advancement of a species. The life forms above are exemplars among all the user species of engineering, but only human engineering leads to new creations that lead to remarkably significant user advancements.

Modern humanity is 300 thousand years old; human languages date from 50 thousand years ago, while Homo sapiens were chipping sharp tools from rocks 3.5 million years ago. Humankind's position among all life forms was not preeminent 3.5 million years ago. This outcome evolved to dominance through humankind's incessant "creation for users," through new thoughts, capabilities, and values to fulfill "user needs" to advance human life, knowledge and prosperity. Other life forms could not compete with humans because their capacity to adapt in thought, opportunity, action and understanding their needs were limited. It is a long, dominant human engineering story that has led to today's advancement of the species and not to extinction. Consequently, over the millennia, which bring us to today, where we can now ask how human engineering should use its dominant global position to preserve rather than exploit the planet in the 21st century. This is the ultimate question underlying this paper.

Summary

The 20th century was such a remarkable period of engineering achievements that the turn of the century inspired the National Academy of Engineering (NAE), in cooperation with 27 US professional engineering societies, to recognize, rank, and memorialize its top-20 engineering achievements. The NAE [1] published the achievements volume titled *A Century of Innovation: Twenty Engineering Achievements That Transformed Our Lives* in 2003 and summarized at http://www.greatachievements.org/. The volume with photographs of the time that enhanced understanding of the period made its information accessible to the public. The professional societies individually ranked the achievements in their descending order of importance leading to their collective ranking of them shown in Table 1. The list was inspirational for many because the achievements all occurred in just 100 years.

Almost immediately upon the volumes publication, engineering creations in the 21 century became of interest, because this is a century of accelerating technological change. Consequently, in 2007, the NAE created an 18-person international committee[†], chaired by William Perry of Stanford University, to envisage what extraordinary engineering creations might be forthcoming in the 21st century. However, the committee concluded that credibly identifying and ranking extraordinary engineering creations over the new century could only be realized retrospectively, and that accelerating change in the 21st century precluded even predicting the areas of greatest change, let alone foretelling the most significant among them. As an alternative, the committee proposed that it could address "what engineering needs to achieve in the 21st century" based on current understandings of the engineering challenges of our time, not a trivial charge.

When the committee undertook this statement of charge, it recognized two overlaying constraints on 21st century engineering predictions. First, in 2007, engineering was already a global enterprise and not a local or national one, and accordingly a century-long *vision* for engineering must view engineering globally—a historic first. Second, every area and scale of engineering is describable using just four English words that link the technical part of engineering, creation and solutions, to the user part of engineering, people and society. However, through the 20th century and earlier, only two words, creation and solutions, characterized engineering education in the United States and engineering itself

[†] Grand Challenges for Engineering Committee: William Perry, chair; Alec Broers, Farouk El-Baz, Wesley Harris, Bernadine Healy, W. Daniel Hillis, Calestous Juma, Dean Kamen, Raymond Kurzweil, Robert Langer, Jaime Lerner, Bindu Lohani, Jane Lubchenco, Mario Molina, Larry Page, Robert Socolow, J. Craig Venter, and Jackie Ying.

https://doi.org/10.1016/j.eng.2020.06.001

Table 1
20th century transformational engineering achievements.

Rank	Achievements
1	Electrification of society
2	Automobile
3	Airplane
4	Water supply and distribution
5	Electronics
6	Radio and television
7	Agricultural mechanization
8	Computers
9	Telephone
10	Air conditioning/refrigeration
11	Interstate highways
12	Space flight
13	Internet
14	Imaging
15	Household appliances
16	Health technologies
17	Petrochemical technology
18	Laser and fiber optics
19	Nuclear technologies
20	High-performance materials

in the minds of many. The technical part of engineering was dominant over the user part shown in Fig. 1.

In my engineering student days a half century ago, many students were attracted to engineering so that they would not have to deal with people and society (organizations of people). The humanistic and social science parts of engineering education were openly of lower priority and even disconnected from the technical parts. This reality has had renowned negative consequences. First, engineering education disconnected engineering students from the users of engineering, and the users of engineering disconnected from engineering too. By not recognizing that serving users, people and society, is *the explicit responsibility of engineering*, engineering education was incomplete, or worse yet, misleading. Regular surveys of the US publics' view of engineering verify that most of the public do not believe that engineers are concerned with social issues. Second, to correct this deficiency in understanding engineering in the *vision* for the Grand Challenges for Engineering in the 21st century, the "user part" of engineering must feature prominently as the destination in the engineering system *vision* statement.

The *vision* statement below is the destination of the engineering system solution that provides the user needs achieved through satisfaction of *goals* by the *objectives*. The engineering design, and its performance and operation specifications, created together, relate the order of the *vision*, *goals*, and *objectives* of the system as shown in Fig. 2.

The Perry committee's primary tasks were to create a global, century-long *vision* for the Grand Challenges for Engineering that identifies the user part of engineering, people and society, as explicitly served by the technical part, creation and solutions. The *vision* statement for this problem expresses their "people and society" destination of the engineering system solution. The 15-word statement captures the key commitments to users: planetary vision; continuation of human life on the planet; advancing services to users in areas of sustainability, security, health, and joy of living or some measure of quality of life.

The *goals* referred to in Fig. 2 are the "technical initiatives" specifically chosen so that their solutions, obtained through *objectives*, when taken together, ensure satisfaction of the above *vision* statement, the key commitments to users. The number and specification of the *goals* span the outcomes required to satisfy the *vision*. The particular *goals* that satisfy achievement of the *vision* are not necessarily unique. The *objectives*, when taken together, satisfy each *goal* over its specified range of inputs. The

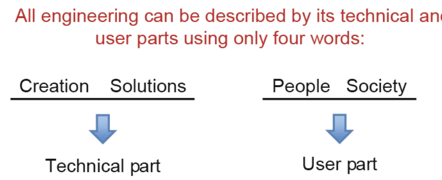

Fig. 1. Technical and user foundations of engineering.

Vision: Continuation of life on the planet, making our world more sustainable, secure, healthy, and joyful

Goals: Grand Challenges for Engineering

Objectives: Solutions that deliver each *goal* (the hard part)

Fig. 2. The hierarchy and roles of the *vision*, *goals* and *objectives*.

engineering design, and its performance and operating specifications, created together, form the *vision*, *goals*, and *objectives* of the system.

Vision—Grand Challenges for Engineering

Based on the committee's deliberations and conclusions, the *vision* presents the destination of the Grand Challenges for Engineering or succinctly here, the user issues that "engineering needs to achieve in the 21st century." The *vision* stipulates the *user benefits* from engineering, the people and society issues, but not the technical issues to achieve them. Accordingly, the *vision* is the non-technical part of the engineering system solution that the general user can understand. Because the technical foundation addressed by the *goals,* delivers the *vision*, the *vision* is the foundation of the system problem. Without a *vision,* there is no specified destination for the system solution. I drafted the *vision* statement above directly from the materials expressed in the Perry committee's report and the *goals* presented therein and here. That report did not present a *vision*, but if it had, it would likely be similar to the one here. The *goals* are the *technical part* in the committee's report whose individual solutions, by design, will fulfill the user needs called for in the *vision*. The 14 individual *goals*, shown in Table 2, satisfied by the creation of their solutions are termed the Grand Challenges for Engineering.

In an extreme case, chosen to aid the discussion of this point, achieving this *vision* statement everywhere would advance human life on the planet everywhere through increased sustainability, security, health and joy, or quality of life. While it would advance the planet in these four domains, it does not claim to eradicate or to avoid influencing any problem. Advancement of life on the planet in the four domains does not preclude local inequities of advancements. However, the *vision* does address how engineering serves people and society explicitly through satisfaction of the *goals* and by reaching the destination.

Goals—Grand Challenges for Engineering

The *goals* shown in Table 2 are technical problems identified by the Grand Challenges Committee whose simultaneous solutions satisfy the *vision* stipulations to achieve sustainability, security, health, and joy of living. Should the domain of the set of solutions to the *goals* enlarges, the domain of satisfaction of the *vision* enlarges and conversely. For domains where solutions to *goals* are not all simultaneously obtainable, achievement of the *vision* requires evaluation on a case-by-case basis.

Table 2
21st century Grand Challenges for Engineering.

No.	*Goals*
1	Make solar energy economical
2	Provide energy from fusion
3	Develop carbon sequestration methods
4	Manage the nitrogen cycle
5	Provide access to clean water
6	Restore and improve urban infrastructure
7	Advance health informatics
8	Engineer better medicines
9	Reverse-engineer the brain
10	Prevent nuclear terror
11	Secure cyberspace
12	Enhance virtual reality
13	Advance personalized learning
14	Engineer the tools of scientific discovery

The Perry committee found that creating solutions to the 14 *goals* in the domain was the minimum set needed to fulfill the *vision*. As you review these *goals*, you will be able to associate them with serving one or more of the four *vision* expectations—sustainability, security, health, and quality of life. Advancing solutions to the *goals* advances satisfaction of the *vision*, the user destination and service to people and society. Other *goals* might also ensure achieving the *vision*, and therefore could be alternative candidates to deliver the *vision*. The *goals* are not necessarily unique and additional factors, such as cost, availability, reliability, safety, and others may become attractive alternatives.

Objectives—Grand Challenges for Engineering

Following establishment of the *vision* and *goals*, the creation of the solutions to each *goal* through the *objectives* follows as shown in Fig. 2. The Perry committee did not propose *objectives* to satisfy each *goal* or rank the relative importance of each *goal* to achieving the *vision*.

Let us propose that the *objectives* present two different, but reasonable solution perspectives. In one, the *objective* for each *goal* is an "engineering system problem" where an *initiative group* of engineers exists that possesses all the necessary competencies to develop the *objective* solution for that *goal* and does so, as shown in Fig. 3. In the second, an engineering *talent group* exists that at present does not possess the mastery required to develop the *objective* solution of each *goal*. The *objective* for this *talent group* would require first preparing its workforce to undertake the engineering system initiative, then subsequently doing so and developing the *objective* solution. Because this is a long-term, global problem, the options to both prepare workforce with the competencies required for the *objectives* (*talent group*) and to reach out to the workforce that possesses competencies needed for the *objectives* (*initiative group*) appear workable. Ultimately, the *talent group* will prepare the workforce for the *initiative group* or they will simply merge.

Grand Challenges Scholars Program creating the *talent group*

In 2008, when the NAE published the *Grand Challenges for Engineering* [2], the Perry committee presented the *vision* and *goals* only and did not discuss achieving, ranking, or implementing the *goals*. Further, it stepped away from creating solutions to the Grand Challenges for Engineering, leaving solution to the *goals* and the delivery of the *vision* to others that followed. Almost immediately, Thomas Katsouleas and Yannis Yortsos[†], and Richard Miller[‡]

[†] Deans of engineering at Duke and USC, respectively, at the time.
[‡] Former President of Olin College of Engineering.

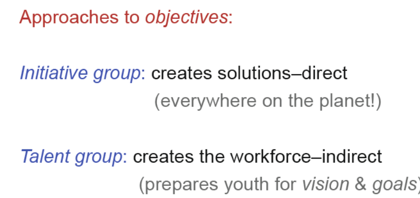

Fig. 3. *Objectives* deliver each *goal* through *initiative* and *talent groups*.

concluded that if engineering is moving to implement the *vision* and *goals* of the Grand Challenges for Engineering in the 21st century, now is the time to introduce engineering students and engineering education systems to them. If the Grand Challenges for Engineering is to influence 21st century engineering, then todays' students will be the engineers who will likely make that happen. Consequently, they created the Grand Challenges Scholars Program (GCSP) to prepare university students with the understanding and competencies needed to undertake a Grand Challenges for Engineering adventure because current engineering education curricula, overall, do not do so. The GCSP has the potential to move engineering and engineering education to become more central to global societal needs in the 21st century.

Their GCSP is an educational supplement to any engineering program that prepares multicultural, multidisciplinary student teams to create solutions to global problems serving people and society—in short; it prepares students for the global *vision* of the Grand Challenges for Engineering. University participation in the GCSP has been expanding since its proposal in 2009.

The GCSP, shown in Fig. 4, has four features that are fundamental to the ultimate success of the Grand Challenges for Engineering. First, the GCSP is a supplement to *any* traditional engineering program offered by any university in any country. It empowers student understanding and preparation for collaborative, multicultural, multidisciplinary global engineering initiatives of our time, like, but not limited to, the Grand Challenges for Engineering. As an educational bridge, the GCSP extends any *national* engineering program into a *global* one. Second, the program facilitates student *understanding* of the Grand Challenges for Engineering that prepares them to inspire communities around the world about them. Third, adoption of the *vision* of the Grand Challenges for Engineering literally depends on the successful, global expansion of the GCSP because it will be these current students and their successors who will carry the Grand Challenges for Engineering ideas forward to their communities, universities, and societies located around the world. In so doing, they could *help shape the future of engineering education* globally. Fourth, after completing their university studies, students who wish to continue their association with the GCSP as professionals and/or volunteers will have an opportunity to do so through the growing GCSP community that supports the coming generations of students.

For implementation, the GCSP must be clear, simple, and focused on necessary student competencies, that are normally not a part of the current course of study in engineering. Student *competency* is what the *student derives* from an educational experience. For the student, the GCSP is not about administration of the program. Each participating university administers its own program. Each university decides: Which students to admit to its program; the method of teaching and evaluating each student competency; whether a student's achievement in each competency merits certification of the student as a *Grand Challenges Scholar;* and recommends to the president of the US NAE each student qualifying for recognition as a Grand Challenges Scholar. The NAE president then responds with a personal letter of congratulations recognizing each qualifying student as a Grand Challenges Scholar.

- Characteristic of the program: *program* and *experiences* supplementing engineering education to underpin Grand Challenge problem solutions→based on student competencies
- University role in the program: each university admits its students, prepares its students, and determines their competency in each of five areas
- Five student "competency" areas in all GCSP programs:
  1. Talent competency–mentored research/project experience on a Grand Challenge-like topic
  2. Multicultural competency–understanding the social viability required for all solution implementations in the intended culture
  3. Multidisciplinarity competency–understanding/appreciating multidisciplinarity gained primarily when creating team-based solutions and experiences
  4. Business competency–creation of viable business/entrepreneurship models required for local solution implementation
  5. Social consciousness competency–understanding the program serves the needs of people and society, such as through service learning and engineers without borders

Fig. 4. The GCSP—summary.

To host a GCSP, the application is on the GCSP website at (www.engineeringchallenges.org/GrandChallengesScholarsProgram.aspx). It requests information in the application about the university's plans for selecting students, ensuring student development in the five competencies described in Fig. 4, and its commitment to a successful program.

Student competencies

The GCSP competencies, shown in Fig. 4, are normally a supplement to any education program that prepares students to engage globally in joint engineering collaborations with students and professionals from other countries[†], an important capability for 21st century engineering. Because student outcomes are the program basis and not administrative procedures, any program can utilize this educational supplement. Each university determines its administrative procedures. Each university decides: who to admit into its program, how to prepare them, and ultimately students' competencies in each of the five outcome areas shown in Fig. 4. Most are not a normal part of an engineering curriculum.

Students ultimately gain true understanding of the five competencies primarily through their personal engagements with others from different cultures, disciplines, and points of view. In his famed analects more than two millennia ago, Confucius provided counsel on this point when he wrote, "I hear and I forget. I read and I remember. But I do, and I understand." Understanding these competencies gained through personal engagement (doing) is not simply listening, reading, writing or sharing responsibilities. The interpersonal engagements highlight both the complexities and the necessity of adaptations for successful collaborations in our globally connected world.

Each host university owns and operates its approved GCSP. Program design around a Grand Challenge theme will ensure coherence and connectivity across the five competencies. The GCSP is outcome based and flexible—it is not prescriptive. The idea of the "21st century engineer" ensures flexibility afforded to the institutions for program execution.

The NAE's role is to inspire and catalyze the movement, champion the vision, convene stakeholders and interested parties, engage the community, and serve as an agent of change. The NAE has no responsibility for the operation of any GCSP and does not financially support any GCSP. It hosts the committee that approves new programs, maintains records, and hosts regional meetings periodically. It also hosts an annual meeting for all GCSPs that also includes those who may be interested in developing a program. It also facilitates understanding and expansion of the number of GCSPs globally serving the ultimate success of the program. However, each program is independent of the NAE and of other GCSPs.

GCSPs sites

As of 16 December 2019, 75 university sites in the US hosted approved GCSPs or ones under review and another 83 university sites have expressed interest in developing a program. Internationally, 17 university programs have approved programs or ones under review and another 53 are exploring creating a program. Of the international programs, those with approved programs or ones close to approval are located in Abu Dhabi, Australia, Brazil, Canada, China's mainland, Hong Kong and Taiwan of China, Italy, India, Lebanon, Malaysia, the Netherlands, Romania, Singapore, and United Kingdom. Other countries and regions, such as Colombia, Indonesia, Israel, Ireland, Kazakhstan, Russia, Republic of Korea, and Vietnam are exploring developing a program as well.

A global ecosystem of GCSPs, as a network of diverse, independent, individual programs in a symbiotic relationship with other programs interested in adapting best practices learned from each other, is highly desirable. The global expansion of this ecosystem to reach younger engineers through the GCSP is also highly desirable for achieving the global implementation of the Grand Challenges for Engineering.

Engineering students express the greatest interest in the global GCSP because they often see it as the current direction of the engineering world and of their professional future. The GCSP introduces opportunities for students that they might not otherwise have, such as:

- Working on a global vision with global solutions;
- Introducing people and society and creating global engineering solutions, as expectations of engineering;
- Recognizing culture as critical to the viability of engineering solutions;
- Understanding that economic considerations are often a determinate of solution viability;
- Realizing that multidisciplinary, multicultural engineering teams undertaking complex system solutions are often transformative;

[†] The great majority of engineering educational programs educate their students to undertake engineering in the culture of their country, even though engineering, as a global enterprise, almost ensures that engineering students today will work globally in the 21st century whether they believe so or not.

- Preparing to engage globally in an engineering career beyond the Grand Challenges for Engineering; and
- Understanding why the *vision* of an engineering initiative is often controlling.

Closing observations

(1) The Grand Challenges for Engineering is a global initiative formed by the assembly of local solutions. An initiative spanning the globe, or even a small country, requires a coordinated assembly of many local solutions.

(2) Over half of the US GCSP students are females and minorities who are naturally attracted and inspired by the user-focus on people and society.

(3) Preparing undergraduate students for global challenges is not a normal feature of engineering education even though it is likely that they will benefit substantially from that preparation.

(4) Students today are receptive to a *vision* of engineering spanning both its technical and user responsibilities covered by the GCSP.

(5) The GCSP extends any national engineering program into a global one that prepares students for multicultural, multidisciplinary initiatives that serve people and society.

(6) Any university, anywhere in the world can implement a GCSP.

(7) The GCSP is important for engineers today because it prepares them for the world's 21st century engineering problems.

(8) Achievement of the *vision* of the Grand Challenges for Engineering depends on global adoption of the GCSP for that outcome both prepares engineers to achieve the *vision* of the Grand Challenges for Engineering and extends its global reach through the GCSP.

References

[1] Constable G, Somerville B. A century of innovation: twenty engineering achievements that transformed our lives. Washington, DC: Joseph Henry Press; 2003.

[2] National Academy of Engineering. NAE grand challenges for engineering. Washington, DC: National Academy of Engineering; 2008.