Extraordinary Engineering Impacts on Society: Over Seven Decades of Contributions from the National Science Foundation: A U.S. National Academy of Engineering Study

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Abstract

The engineering profession is tightly linked with its societal impacts, applications, and benefits. However, these impacts of engineering often remain unclear and misunderstood by the general public. To enhance public awareness about the impacts of engineering and the influence of federal support in bringing them about, as well as to help attract a more diverse engineering workforce, the National Science Foundation (NSF) tasked the National Academy of Engineering (NAE) with conducting a consensus study exploring the "extraordinary" societal impacts of engineering. For this study, the NAE formed a 12-member expert interdisciplinary committee with a mandate to identify extraordinary engineering impacts; organize a virtual public symposium on the topic; develop clear, compelling narratives for public engagement; and provide guidance on how to reach and engage diverse audiences with these narratives. Prior compilations of the NSF's impacts such as those released for the agency's 50th and 60th anniversaries (the "Nifty 50" and "Sensational 60" lists, respectively) celebrated technocentric breakthroughs, such as buckyballs and fiber optics. However, this new NAE study takes a distinct approach, highlighting the stories of engineers and programs that have had exemplary societal impacts. A particular emphasis is placed on individuals historically underrepresented in the engineering profession, including people of color, women, and people with disabilities, bringing their experiences and achievements to the forefront. Slated to be released in mid-2024, the report's findings, conclusions, and recommendations are not yet available. However, this article aims to shed light on the various ways that the NSF and NAE have conceptualized engineering's impacts on society by 1) exploring the history of engineering at NSF, 2) analyzing foundational material from the NSF/NAE that informed the work of the committee such as NSF's Broader Impacts and NAE's Grand Challenges in Engineering, 3) and comparing these to content from the new study that is publicly available. An additional aim of this article is to raise awareness of the upcoming NAE report and encourage thought-provoking discussions about it at the ASEE 2024 Annual Conference.

Introduction

Engineering has long been characterized by the benefits it imparts on society. As early as the 1800's when American engineers began to delineate professional guidelines and codes of conduct, engineering has been associated with "societal uplift" [1, p. 2]. Current day, the foremost engineering professional societies have similar mission and vision statements such as "advancing engineering for the benefit of humanity" [2], "engineered and natural systems work[ing] in harmony for the benefit of humanity" [3], and "foster[ing] technological innovation and excellence for the benefit of humanity" [4].

While it's widely promoted that engineering is closely tied to societal impacts, the specific benefits it brings about are less clear. Surveys conducted in the U.S. have revealed a prevailing lack of awareness regarding the role of engineering in enhancing quality of life. For instance, a 2004 survey found that engineers were ranked behind scientists in terms of community engagement, sensitivity to societal issues, and saving lives [5]. This trend is particularly pronounced among K–12 students, who may recognize that engineers design and construct mechanical systems and structures, but typically overlook the diverse array of tasks and fields in which engineers operate [6]. Scholars have raised important questions like "what is engineering for?" [7, p. 361] and "who is served by the development of different technologies, products and infrastructures?" [1, p. 1].

To help address these issues, the National Science Foundation's (NSF) Directorate for Engineering tasked the National Academy of Engineering (NAE) with conducting a study that would "highlight how fundamental engineering research has led to positive societal and economic impacts" [8]. As an independent body, the NAE convenes experts to offer guidance to the nation, including sponsors like the NSF, on matters crucial to engineering and technology. Thus, in 2020 the NAE formed an *ad-hoc* expert committee tasked with 1) identifying up to ten significant engineering impacts from NSF investments since its founding in 1950, 2) organizing a virtual public symposium, 3) developing engaging narratives for public understanding, and 4) providing guidance on reaching diverse audiences and encouraging youth to pursue engineering careers. Emphasis was placed on highlighting exemplary stories and individuals.

The forthcoming NAE report will offer conclusions and recommendations on how to best promote an understanding of engineering's contributions to society and the role the NSF plays in those contributions [9], and is anticipated to be available prior to the 2024 ASEE Annual Conference. As of early 2024, the final report is still in preparation and its findings are not available for presentation. Therefore, this paper explores report content that may be publicly discussed, as well as other resources from the NSF/NAE that were foundational references for the report committee, such as NSF's Broader Impacts and NAE's Grand Challenges in Engineering. This article's goal is to illuminate the various ways that the NSF and NAE have conceptualized engineering's impacts on society by comparing the new NAE study's approach to previous, similar efforts from both organizations along with the history of engineering at NSF. While the conceptualization of these societal impacts is crucial to public communication of engineering, communication will not be the primary focus here. Instead, this article aims to raise awareness of the upcoming report to encourage discussion and feedback at the 2024 ASEE Annual Conference.

Background

The Evolution of Engineering Support at NSF

Established in 1950, the NSF's stated mission was to "promote the progress of science; advance national health, prosperity and welfare; [and] secure the national defense" [10]. Given that other federal agencies (e.g., the Department of Defense, Department of Energy) already supported applied research, the NSF became the only federal sponsor of basic, fundamental research. As a result, the NSF was uniquely positioned to "free science pursuing its independent way to unravel the mysteries of existence, carried on by free men whose guide is truth and whose faith is that it is good to know" [11, p. 2839].

The role of engineering at NSF has long been characterized by tensions between "basic" and "applied" research [12], [13], with engineering frequently falling under the latter. Despite its applied nature, engineering was present at NSF since the onset. Of the $1.1 million that went to research grants in NSF's 1952 research budget, engineering projects received about $42,000 through the Division of Mathematical, Physical and Engineering Sciences, and accounted for 75 of the 624 original graduate fellowships [14, p. 44]. For 2024, the NSF requested a total of $11.314 billion in funding from Congress [15], with $970 million for the Engineering Directorate, notwithstanding support for engineering projects within other directorates, demonstrating the significant expansion of engineering at NSF over the last 70+ years.

The launch of Sputnik by the Soviet Union in 1957 significantly changed the trajectory of engineering research and education within NSF and the U.S. in general [12]. The perception that the Soviets had surpassed the U.S. in critical areas of science and technology drove major increases in investments for engineering research and education. In a single year, NSF funding for engineering research went from $1.5 million to $4.2 million [16, p. 45], [17, p. 54], and for the first time the National Defense Education Act of 1958 authorized federal aid for engineering education [18, p. 41]. In 1964, the Division of Engineering was established at NSF, the same year the NAE was founded, signaling a heightened recognition of engineering's role in addressing national defense challenges.

Throughout the 1960s and 1970s, NSF's focus on engineering intensified with more programs aimed at addressing national needs through applied research. In 1963, shortly before President Kennedy's assassination, he voiced his opinion that "scientists alone can establish the objectives of their research, but society, in extending support to science, must take account of its own needs" [8, Ch. III], [12]. Despite facing criticism for diverting funding from fundamental research, "the elitism embodied in the science-government relationship dating to the post-World War II years had to give way to a broader, more democratic base" [8, Ch. III].

This era demonstrated a concerted effort by NSF to address "human problems" affecting citizen's everyday lives. Initiatives like the controversial Research Applied to National Needs (RANN) program (1971-1978) supported research on domestic societal challenges. Bazell asserted in 1971 that "America might drown in sewage, choke on polluted air, run out of fuel, or fall into chaos from crime in the streets. But nobody will be able to say the National Science Foundation didn't try to help" [20, p. 1315]. RANN was largely supported by the engineering community, and in 1973 the NAE published a report with recommendations for priority focus areas for RANN [21]. The report emphasized that "[RANN] must deal with 'human' problems which are scarcely tractable and which cannot be resolved with the speed and dramatic success possible in such essentially technical areas as aerospace and military weaponry" (p. vi), suggesting that RANN ought to "lead the way in developing effective means of integrating applied social science, physical science, and engineering research" (p. iii).

In 1981, NSF met congressional calls to elevate the significance of engineering within NSF by establishing a Directorate for Engineering (ENG). This move came amidst growing concerns about U.S. technical competitiveness in global markets, particularly given the rapid development of the Japanese economy [12]. The aim of this directorate was to enhance the technology initiatives of the NSF while fostering strong links between engineering research, education, and industry. Notably, in 1984 the Engineering Directorate established the Engineering Research Centers (ERC) program which continues today. The ERC program is lauded for facilitating interdisciplinary research, advancing technology, preparing generations of engineering professionals and leaders, and enabling research breakthroughs to move from labs to market [13].

Since the 1980s, ENG has expanded significantly. Engineering research has also become central to other new directorates, such as the Directorate for Technology, Innovation, and Partnerships (TIP) established in 2022. The CHIPS bill formally codified this new directorate into law, the first in over 30 years, and authorized $81 billion in new funding for NSF from 2023-2027 [22], a substantial portion of which will go towards TIP's support of domestic semiconductor engineering and production. TIP aims to "[harness] the nation's vast and diverse talent pool to advance critical and emerging technologies, address pressing societal and economic challenges, and accelerate the translation of research results from lab to market and society. TIP improves U.S. competitiveness, growing the U.S. economy and training a diverse workforce for future, high-wage jobs" [23]. While the growth of engineering at NSF highlights engineering's crucial role in national defense and economic competitiveness, the scope of "societal impact" extends beyond these domains.

NSF's Broader Impacts

To help grasp the breadth of the societal impacts of scientific and engineering research, it is useful to delve into NSF's own guidelines known as the "Broader Impacts Criteria" (BIC), which were foundational in the preparation of the forthcoming NAE report. Broader Impacts are one of two main pillars by which all NSF funding proposals are assessed, alongside "Intellectual Merit." The Broader Impacts requirement was officially introduced in 1997, and in 2002 the NSF began returning proposals without review if they didn't mention Broader Impacts [24]. The implementation of Broader Impacts stemmed from recommendations from the Committee on Equal Opportunities in Science and Engineering; the passing of the Government Performance and Results Act; and the "NSF in a Changing World" strategic plan [25] that outlined a long-term goal of promoting knowledge in service of society. Currently, NSF is the only federal agency that has such a requirement for its proposals.

A Broader Impacts statement must address a project's potential to "benefit society and contribute to the achievement of specific, desired societal outcomes" [26]. While NSF "does not want to be prescriptive about the societal outcomes a project addresses," they want to ensure that public funding goes toward research with "tangible benefits to society that go beyond increasing knowledge" [27]. The current NSF website [27] provides several examples of BIC that may include but are not limited to:

- inclusion;
- STEM education;
- public engagement;
- societal well-being;
- STEM workforce development;
- partnerships between academia, industry and others;
- national security;
- economic competitiveness; and
- infrastructure for research and education.

While BIC have always been expansive, scholars have delineated common categories of Broader Impacts in accepted proposals. Verdín [28] analyzed BIC proposed in 82 project summaries accepted by NSF's Division of Engineering Education and Centers, identifying categories with respect to the 2016 Proposal and Award Policies and Procedures Guide. Roberts [24] analyzed and coded 294 project summaries from NSF research awards from 2006 to 2008, noting a divide between "Broader Impacts for science" and "Broader Impacts for society," based on the 2007 NSF guidelines for proposal preparation.

Table 1. Categories of BIC, adapted from Table 1 in [24] and Table 2 in [28].

BIC in Roberts [24]	
BIC for "science"	**BIC for "society"**
Infrastructure for science	Potential societal benefits[1]
Broadened participation	
Training and education	Outreach/broad dissemination
Academic collaborations	
K-12 outreach	Partnerships with potential users of research results
BIC in Verdín [28]	
Increase public scientific literacy	
Increase public engagement with science and technology	
Broadening participation	
Develop a diverse STEM workforce	
Develop a globally competitive STEM workforce	
Increase economic competitiveness of the U.S.	

[1] Proposals "that discussed how the research could help to address a societal problem or industrial or policy need. Descriptions of how results could improve understanding of a natural

process, such as climate change, that did not directly state how the results could be useful to fix a problem or inform policy, were not counted as potential societal benefits" [24, pp. 207-208].

While the categories of BIC are often similar, scholars have found mixed results on the distribution of cited Broader Impacts across the various categories. Verdín [28] found that the top three BIC were increased public scientific literacy, public engagement in science and engineering, and developing a diverse STEM workforce. However, Watts et al. [29] found that activities aimed at broadening participation of underrepresented groups in STEM fields were less frequently reported. Kamenetzky [30] reported that teaching and training were commonly cited, followed by broad dissemination and infrastructure enhancement. Cultural differences among STEM fields and political considerations may play a significant role in the types of broader impacts mentioned or omitted in research proposals [24], [30] . Roberts [24] found that researchers who mentioned societal benefits in their proposals were not more likely to propose dissemination of their results to relevant stakeholders compared to those who only addressed Broader Impacts for science, suggesting a gap between the proposed societal benefits and actual dissemination of research beyond the scientific community.

While the creation of NSF's BIC and efforts to build institutional capacity around them have made strides in linking research to societal impacts, there is room for improvement. Bozeman [31] suggested assessing who benefits from NSF-funded research and establishing metrics for Broader Impact assessment. Without such analysis, NSF-funded research could perpetuate or worsen existing inequalities [32]. The Inclusion-Immediacy (IIC) framework developed by Woodson and Boutilier [33], for example, aims to address this gap by evaluating NSF grants based on the alignment of proposed Broader Impacts with the beneficiaries of the research, particularly historically marginalized communities.

Engineering "Greatest Hits" Compilations

Because the Broader Impacts are intentionally broad, it is helpful to juxtapose them with projects considered successful by various parties to gain a clearer understanding of the specific societal impacts that are most valued. Both the NSF and NAE have published compilations of such notable projects or areas of high impact, what may be termed as their "greatest hits." There are numerous reports, lists, articles, and even artworks highlighting advances brought about by federal funding for engineering. The following greatest-hits-lists are cited as salient references informing the new NAE study. While we do not cover every impact mentioned in the resources below, we aim to emphasize how these impacts are presented and touch upon some of the overarching themes.

In 2000, the NSF released the "Nifty Fifty" list in honor of their 50^{th} anniversary—"NSF-funded inventions, innovations and discoveries that have become commonplace in our lives" [34]. Of these breakthroughs, at least 22 have direct ties to engineering[1]. A decade later, in celebration of

[1] Bar Codes, Buckyballs, CAD/CAM, Computer Visualization Techniques, The Darci Card, Data Compression Technology, Doppler radar, Earthquake Mitigation, "Eye Chip" or Retina Chip, Fiber Optics, The Internet, MRI:

its 60th anniversary, the NSF compiled a list of sixty significant advancements—the “Sensational 60”—that “have had a large impact or influence on every American’s life” [35]. This new list included several new engineering-related innovations that weren’t part of the Nifty Fifty[2]. In its latest milestone, NSF marked its 70th anniversary by commissioning a mural to visually narrate the impact on society of research supported by the agency ([36], Figure 1), a piece referred to as the “History Wall”. Completed in 2022, the mural showcases numerous entries from the aforementioned lists, along with additional engineering-related accomplishments[3].

Figure 1. “History Wall” [37].

The Nifty Fifty, Sensational 60, and History Wall websites include descriptions of the research and impacts for each item. These impacts on “every American’s life” [35] are sometimes implied and sometimes explicit. For instance, #9 on the Nifty Fifty, “CAD/CAM,” explicitly states that “without this very sophisticated CAD software, it would not be possible to design, build and verify the complex integrated circuits that power the information technology age in which we are living” [35], [38]. Also apparent, the History Wall explains how support for the “Magic School Bus” TV program has “facilitate[d] elementary and informal STEM education.” On the other hand, #4 on the Sensational 60, “Arabidopsis—A Plant Genome Project,” describes how plant gene research led to the development of crops with improved cold tolerance and yield. While the societal impact is not stated outright, it is implied that these advances have led to greater food security, for instance.

The NAE has compiled texts like the “Twenty Engineering Achievements that Transformed our Lives” [39], released in 2000, which was asserted to be “proof positive that the genius and the

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[1]Magnetic Resonance Imaging, Microburst Research, MEMS: Microelectromechanical Systems, Nanotechnology, The Partnerships for Advanced Computational Infrastructure (PACI) Program, Persons with Disabilities Access to the Web, Reaction Injection Molding, Speech Recognition Technology, Tissue Engineering, vBNS: Very High Speed Backbone Network System, Volcanic Eruption Detection, and Web Browsers.

[2] Biofuels and clean energy; clean and adequate water; cloud computing; deep-sea drilling; RSA and public-key cryptography; speech recognition technology; supercomputer facilities

[3] NSF-funded search-and-rescue robots for improved disaster response; NSF’s [Small Business Innovation Research] SBIR program for strengthening the role of small business in federally funded R&D, as it did in cellular technology in the 1990s; in electronics and material science, graphene’s unique electrical and physical properties which promise new breakthroughs; *Robobees,* innovative autonomously flying microrobots that have potential impacts in many applications; discovery of quantum phenomena that can yield novel technologies in computing and communications; 3D printing for its impacts on manufacturing, design, and the arts; support for programs like “The Magic School Bus,” that facilitate elementary and informal STEM education.

talent of the world's engineers have truly transformed the way people live"[4] (Table 2). Summaries of the societal impacts brought about by these achievements include how electrification "provide[s] power for the developed world," water supply and distribution advances "prevent the spread of disease, increasing life expectancy," and household appliances "have eliminated many strenuous, laborious tasks, especially for women," [40, pp. 2–3].

Table 2. Twenty Engineering Achievements that Transformed our Lives, adapted from [39].

1. Electrification	11. Highways
2. Automobile	12. Spacecraft
3. Airplane	13. Internet
4. Water Supply and Distribution	14. Imaging
5. Electronics	15. Household Appliances
6. Radio and Television	16. Health Technologies
7. Agricultural Mechanization	17. Petroleum and Petrochemical Technologies
8. Computers	18. Laser and Fiber Optics
9. Telephone	19. Nuclear Technologies
10. Air Conditioning and Refrigeration	20. High-Performance Materials

Other studies conducted by the National Academies of Sciences, Engineering, and Medicine (NASEM) have focused on the economic impacts of funding engineering research. For example, a 1995 NASEM report introduced the "tire tracks" diagram [41], illustrating how federal investments in academic and industry research led to the development of information technology (IT) industries. Widely utilized in presentations to Congress and executive branch officials, the diagram dispelled the misconception that the IT industry flourished independently. Instead, it underscored the significant dependence on government-funded university research and the extended incubation periods often necessary for industry progress. This report inspired five follow-on efforts [42], [43], [44], [45], [46].

In addition to highlighting the impacts of past engineering efforts, the NAE has published forward-looking guidance on "broad realms of human concern [that] await engineering solutions" [47, p. 2]. The "NAE Grand Challenges" report became widely publicized, catalyzing programs like the Global Grand Challenges Summit series and the Grand Challenges Scholars Program [48]. The Grand Challenges are 14 focus areas (Table 3) in which "engineering can address current and emerging societal challenges" [49]. There is an emphasis on sustainability in the report, acknowledging "the problem of sustaining civilization's continuing advancement, while still improving the quality of life" [47, p. 2]. The Grand Challenges have been divided into four cross-cutting themes: sustainability, health, security, and joy of living [50], akin to four realms of societal impact.

[4] From: https://nap.nationalacademies.org/catalog/10726/a-century-of-innovation-twenty-engineering-achievements-that-transformed-our

Table 3. NAE' Grand Challenges in Engineering, from [47].

1. Make solar energy economical	8. Engineer better medicines
2. Provide energy from fusion	9. Reverse-engineer the brain
3. Develop carbon sequestration methods	10. Prevent nuclear terror
4. Manage the nitrogen cycle	11. Secure cyberspace
5. Provide access to clean water	12. Enhance virtual reality
6. Restore and improve urban infrastructure	13. Advance personalized learning
7. Advance health informatics	14. Engineer the tools of scientific discovery

New NAE study: Extraordinary Engineering Impacts on Society

Similar to previous efforts, NAE's new study aims to identify examples of extraordinary engineering impacts on society supported by the NSF, increase public awareness and understanding of these impacts, and provide guidance on attracting diverse groups of young people to the consider engineering professions. As part of this work, the NAE hosted a virtual public symposium in August of 2022, featuring 31 speakers from an array of engineering disciplines and backgrounds, all of whom had received NSF support. A complete repository of presentation recordings can be found on YouTube [51] and the symposium proceedings are publicly available [40]. An exploration of the showcased speakers, themes, and projects provides further insight into what the NAE and NSF consider significant societal impacts resulting from engineering research and offers insight into what to anticipate in the upcoming report.

This study distinguishes itself from previous greatest hits compilations by prioritizing individuals and their narratives over a technocentric approach. Although "Twenty Engineering Achievements that Transformed our Lives" also highlighted the stories of people behind significant inventions, they were largely well-known historical figures like the Wright Brothers and Alexander Graham Bell [39]. In contrast, the 2022 symposium showcased speakers and achievements that may not be as widely recognized, with an emphasis on diversity, equity, and inclusion. At the symposium, NAE President John Anderson underscored that "propelling the [engineering] achievements are people, and their stories are as important as the achievements themselves" [52]. NAE's report committee chair, Dan Arvizu, elaborated on the areas impacted by these individuals and their careers—"not just technology and the nation's infrastructure, but the economy, population health, manufacturing services, disaster resilience, and individual qualities of life" [53]. Below are summaries of the speeches of three symposium speakers that aim to encapsulate their narratives and areas of societal impact.

Exemplary Engineers & their Impacts

Karen Lozano shared her journey from Monterrey, Mexico, to becoming an Endowed Professor of Mechanical Engineering at the University of Texas Rio Grande Valley (UTRGV). [54]. In her youth, Lozano was a waitress and sold dresses door-to-door before embarking on her engineering journey. Encouraged by her mother to "pursue the path less traveled" as one of very few women in her program, Lozano earned her PhD in Houston, Texas, and became a faculty member at UTRGV in 1999. Despite being primarily a teaching institution with minimal research focus, Lozano was driven by the opportunity to make a difference through research. Lozano explained that over 90% of UTRGV students are local and from Hispanic backgrounds, with more than 50% first-generation college students and over three-quarters relying on financial aid. In education, the Rio Grande Valley ranks 148^{th} out of 150 metropolitan regions in Texas. Lozano added that in engineering overall, only about 8% of bachelor's degrees go to Hispanic men and about 3% to Hispanic women. Hispanic representation comprises a mere 1% of graduate engineering degrees, underscoring the "imperative need to further engage women and underrepresented minorities in engineering" (p. 49).

In part thanks to support from the NSF in the form of a Major Research Instrumentation grant, an NSF Faculty Early Career (CAREER) award, and a Partnership for Research and Education in Materials (PREM) Center award, Lozano established a flourishing research program at UTRGV on nanofiber composite materials. Since 2009, the PREM center has involved an estimated 500+ students with a 100% graduation rate. As of 2022, PREM had more than 200 peer-reviewed journal publications with 85% of them featuring an undergraduate coauthor, as well as 20+ patents and applications. Lozano stressed the importance of students "establishing that deep connection with a project and their studies and more so with a faculty member that guides and cares for their success" (p. 50). Beyond her remarkable achievements in education and workforce development, which also include extensive K-12 and community outreach, Lozano and her students have contributed valuable advances in nanofibers for applications like tissue engineering, filtration, drug delivery, batteries, and cancer diagnostics. In 2023, Lozano was elected to the NAE for her "contributions to nanofiber research and commercialization, and highly impactful mentoring of students from underserved populations at an undergraduate institution" [55], marking her as the first NAE Member to build their entire career at a non-R1 research institution.

Another symposium speaker was Paula Hammond, an Endowed Chair Professor of Engineering at the Massachusetts Institute of Technology (MIT). She serves as the head of the Department of Chemical Engineering as well as a faculty member at MIT's Koch Institute for Integrative Cancer Research. Hammond holds the distinction of being both the first woman and the first person of color to lead MIT's Chemical Engineering department. During her talk, Hammond reflected on her childhood in Detroit where she developed a fascination with "pulling things apart, including plants and leaves and anything that you could find on the ground" [56]. She said that her father, one of the few Black men with a PhD in biochemistry at the time, and her mother, a nurse and educator, greatly influenced her interest in STEM. Hammond's passion for chemistry led her to pursue both her undergraduate and graduate studies in chemical engineering at MIT.

Some of her earliest research was funded by NSF, including a CAREER award for building thin films with oppositely-charged polyelectrolytes [40]. This evolved into investigating the use of synthetic polypeptide nanoparticles for drug delivery. Leveraging positive and negative outer layer surface charges, Hammond and her team developed nanoparticles with high affinities for specific cells like elusive ovarian cancer cells, effectively containing and delivering drugs to these targets for improved treatment outcomes. Hammond emphasized that her foundational research supported by NSF paved the way for more applied research funded by the National Institutes of Health and Department of Defense.

Hammond has authored over 330 papers and holds more than 20 patent applications. She has significant experience in industry as a co-founder of LayerBio, Inc., and Scientific Advisory Board member of Moderna Therapeutics. Like Lozano, Hammond is passionate about mentoring her students and "see[ing] them evolve and develop their own idea" (p. 36). She has actively participated in programs such as MIT's undergraduate summer research program, advocated for inclusion as the chair of MIT's Initiative for Faculty Race and Diversity, and contributed to international initiatives addressing technological needs in Ghana and Kenya. Her expertise informs national scientific policy as a member of President Biden's Council of Advisors on Science and Technology. Moreover, Hammond is one of only 33 people to have been elected to all three National Academies of Sciences, Engineering, and Medicine [57].

A third symposium speaker was Rory Cooper, Assistant Vice Chancellor and Distinguished Professor of Rehabilitation Science and Technology at the University of Pittsburg (Pitt); as well as Founding Director of the Human Engineering Research Laboratories [40, pp. 66–68], [58] and wheelchair-marathon champion. Having sustained an injury during his U.S. Army service, Cooper has utilized a wheelchair since, turning unexpected challenges into opportunities to inspire others and effect change. His career motto, "nothing about us without us," emphasizes his commitment to involving members of the disability community in engineering the technologies that directly impact their lives. Cooper is an advocate for social mobility, health, and societal participation through technology.

Cooper's extensive involvement with NSF programs has created numerous opportunities for engineering students with disabilities. For over 20 years, Cooper has been helped lead the American Student Placements and Internships in Rehabilitation Engineering (ASPIRE) Research for Undergraduates (REU) summer program, which he regarded as the "diamond in our work." ASPIRE welcomes students who have limited research opportunities at their own institutions, offering them the chance to conduct research at Pitt and equipping them with insights and skills that they can apply in their own schools and careers. For example, Cooper and his students developed a waterproof wheelchair aimed at enhancing accessibility for children in waterparks, opening possibilities for play. In another example, Cooper demonstrated a prosthetic-compatible mouse that can allow amputees to use a conventional computer. The success of ASPIRE led to the creation of similar programs by the Veterans Affairs Department.

Cooper cited other NSF programs he's worked on like Quality of Life Technology Enrichment (QuOTE), which assessed Pitt's institutional support for students with disabilities to enhance their success. The Experiential Learning for Veterans in Assistive Technology and Engineering (ELeVATE) program supported injured or ill veterans in succeeding in engineering or technical programs, leading to changes in the GI Bill that extended study time from four to five years. The Quality of Life Technology Engineering Research Center (QoLT ERC), in collaboration with Carnegie Mellon University, has provided students with experience in design, development, publication, and patenting. Cooper stated that many alumni from these programs, particularly the ERC, have held influential positions in industry and policymaking, advocating for accessible systems and contributing to policy changes at major corporations like Microsoft and Amazon, as well as in federal leadership roles at the VA.

In all three of these examples, the symposium speakers emphasized the critical need to nurture diversity and inclusivity by offering support to underrepresented individuals in the engineering community. They recognized these efforts as pivotal for driving meaningful societal impact through engineering. These speakers, all belonging to underrepresented groups in engineering themselves, highlighted the importance of various NSF programs that aided them and their students in this mission, and illustrated the wide-ranging impacts stemming from their work. These impacts encompassed not only technical advancements such as the development of new materials and advancements in cancer research, but also social progress in fostering greater participation in engineering and enhancing workforce diversity and talent.

Discussion

Engineering studies scholars have long asked the question, *what is engineering for?* [7], [59]. Engineering's impacts on society depend on the answer to that question, which Lucena argued "is often shaped by power relations among those funding engineering research and those involved in educating engineers" [7, p. 362]. This article aims to provide perspective on the NSF and NAE's conceptions of engineering's societal impact through explorations of 1) the historical trajectory of engineering at NSF, 2) NSF's Broader Impacts Criteria, 3) past compilations of notable engineering accomplishments by the NSF and NAE, and 4) content from the new NAE Extraordinary Engineering Impacts on Society study. Through these distinct lenses, an array of societal impacts of engineering emerges (bolded below).

A historical analysis of the NSF's support for engineering illuminates some of the societal impacts prioritized by the federal government. Engineering's critical role in the **national defense, geopolitical competition, economic growth, and meeting taxpayers' daily needs** has been compelling enough to supersede long-standing controversies on engineering's applied nature within an agency created to support fundamental research. In fact, since NSF's inception in 1950, its mission has evolved to explicitly "support solutions-oriented research with the potential to produce advancements for the American people" [10] alongside funding basic research.

To further understand the societal impacts of engineering prioritized by NSF, we turn to the NSF's Broader Impacts Criteria (BIC). Despite prevailing confusion about what the BIC exactly are, the adoption of these criteria demonstrates the agency's commitment to promoting impacts from research beyond knowledge production. Subject to wide interpretation, the BIC generally cover **STEM education; public engagement; broadening participation; research dissemination; workforce development; multi-sectoral partnerships; national security; economic competitiveness; and infrastructure for research and education**. Various scholars have analyzed which BIC are most commonly cited in NSF research proposals with mixed results [24], [28], [30]. Importantly, researchers have noted that proposed Broader Impacts can be influenced by political contexts and cultural differences among STEM fields [24], [30], warranting investigation into the alignment between what researchers say their projects' impacts will be and what they are in practice.

Further information about the societal impacts valued by the NSF/NAE can be gathered by reviewing the lists of projects these organizations promote as extremely impactful—their *greatest hits* lists. A review of these compilations reveals an emphasis on technologies that have become commonplace and have significantly influenced or "transformed" "every American's life," as captured in the Nifty Fifty, Sensational 60, and History Wall. In this case, engineering's societal impact may thus correspond to **the breadth of its "domain of application,"** using the terminology of Blue et al. [60, p. 3]. To understand the specific fields encompassed in this wide domain—i.e. medical breakthroughs, computational advances, agricultural productivity—one can refer to the lists themselves which provide brief explanations for each item. Additional greatest hits examples, like NAE's "tire tracks" reports, are explicit about centering engineering's **economic impacts**. NAE's Grand Challenges report emphasizes engineering's role in "sustaining civilization's continuing advancement, while still improving the quality of life" [47, p. 2]—in other words, engineering for **sustainability**. This description echoes the widely adopted definition of sustainable development from the United Nation's 1987 Brundtland Commission to "meet the needs of the present without compromising the ability of future generations to meet their own needs" [61, p. 16].

The new NAE "Extraordinary Engineering Impacts on Society" study has thus far taken an anthropocentric approach to assessing engineering impacts, focusing on the lesser-known stories of engineers behind important advances with an emphasis on **diversity, equity, and inclusion**. Symposium speakers like Karen Lozano, Paula Hammond, and Rory Cooper are from underrepresented groups in engineering and serve as living examples of why federal investment in **broadening participation** in engineering matters. These individuals have not only contributed to technical advances in areas of material science, cancer treatment, accessibility technology, and more, but have also supported and inspired younger generations of engineers from an array of backgrounds to pursue and succeed in engineering, bolstering engineering capacity nationwide.

When assessing the ways that the NSF and NAE have conceptualized and communicated engineering's societal impacts, it's important to bear in mind the explicit goals of these institutions—to not only highlight societal impacts of engineering research, but to simultaneously garner interest and participation in engineering amongst wide audiences and justify the importance of federal funding for engineering research. Thus, visible, relatable, and positive examples are helpful. The NAE's current mandate explicitly states that the committee should "highlight how fundamental engineering research has led to *positive* societal and economic impacts" [8, emphasis added], and develop narratives to garner excitement about engineering from general audiences, especially young and underrepresented groups. As a result, the forthcoming report will not be an academic examination of the limitations or potential negative impacts on society of engineering and scientific research. While the NSF and NAE have been criticized for not examining such limitations [1], [33], this is out of scope of the statement of task for the study.

Conclusions & Future Work

It is clear that the conceptualization of engineering's societal impact varies widely depending on the audience(s) and objectives of particular organizations and authors. The history of engineering funding at NSF reveals it's impacts on the economy and national defense, of great interest to Congress. NSF has set forth their own goals for areas of impact through the Broader Impacts Criteria, generally related to public scientific literacy and workforce development through education, research dissemination, infrastructure, partnerships, public engagement, and more. The greatest hits compilations from the NSF and NAE seek to appeal to general audiences by highlighting engineering contributions whose impacts are felt in people's daily lives. Lastly, the new NAE study aims to communicate engineering's societal impact to wide audiences through the narratives of diverse and prolific engineers who have been supported by NSF.

This forthcoming NAE report will build upon the 2022 symposium and other salient NAE/NSF efforts. Once the final report is released, future work could delve deeper into the authoring committee's findings, conclusions, and recommendations to the NSF for understanding and communicating engineering's impacts on society. Given the widespread attention at past ASEE conferences to NAE reports such as the Grand Challenges in Engineering [47], we hope that the present article will encourage thoughtful discussions on the topics presented here and in the new report at the 2024 ASEE Annual Conference, aiding future NAE efforts in this field.

References

[1] A. Slaton, "Note to Self: Save Humanity (A Social and Cultural History of the 'Grand Challenges')," in *2011 ASEE Annual Conference & Exposition Proceedings*, Vancouver, BC: ASEE Conferences, Jun. 2011, p. 22.1104.1-22.1104.15. doi: 10.18260/1-2--18812.

[2] ASME, "Mission, Vision, and Strategic Priorities." Accessed: Feb. 08, 2024. [Online]. Available: https://www.asme.org/About-ASME/Mission-Vision-and-Strategic-Focus

[3] ASCE, "About ASCE." Accessed: Feb. 08, 2024. [Online]. Available: https://www.asce.org/about-asce

[4] IEEE, "Mission & Vision." Accessed: Feb. 08, 2024. [Online]. Available: https://www.ieee.org/about/vision-mission.html

[5] M. Baranowski and J. Delory, "Because dreams need doing: New messages for enhancing public understanding of engineering," 2007, [Online]. Available: http://www.ppinys.org/innovation/BBMG-Final-Report-for-Public.pdf.

[6] NAE, *Changing the Conversation: Messages for Improving Public Understanding of Engineering*. Washington, D.C.: National Academies Press, 2008, p. 12187. doi: 10.17226/12187.
[7] J. Lucena, “What is Engineering for? A Search for Engineering beyond Militarism and Free-markets,” in *What is Global Engineering Education For? The Making of International Educators, Part III*, G. L. Downey and K. Beddoes, Eds., in Synthesis Lectures on Global Engineering. , Cham: Springer International Publishing, 2011, pp. 361–383. doi: 10.1007/978-3-031-02125-1_6.
[8] NASEM (National Academies of Science, Engineering, and Medicine), “Our Work: Extraordinary Engineering Impacts on Society: Over Seven Decades of Contributions from the National Science Foundation.” [Online]. Available: https://www.nationalacademies.org/our-work/extraordinary-engineering-impacts-on-society-over-seven-decades-of-contributions-from-the-national-science-foundation#sectionProjectScope
[9] NASEM, *Impacts of NSF Engineering Research Support on Society [working title]*. Washington, D.C.: The National Academies Press, 2024.
[10] NSF, “About NSF.” Accessed: Feb. 08, 2024. [Online]. Available: https://new.nsf.gov/about
[11] D. W. Bronk, “The National Science Foundation: Origins, Hopes, and Aspirations,” *Science*, vol. 188, no. 4187, pp. 409–414, May 1975, doi: 10.1126/science.1091972.
[12] G. Mazuzan, *The National Science Foundation: A Brief History*. Washington, D.C: NSF, 1994. Accessed: Jan. 04, 2024. [Online]. Available: https://www.nsf.gov/about/history/nsf50/nsf8816.jsp
[13] L. Preston and C. Lewis, *Agents of Change: NSF’s Engineering Research Centers--A History*. Potomac, MD: Lynn Preston Associates LLC, 2020. Accessed: Feb. 07, 2023. [Online]. Available: https://erc-history.erc-assoc.org/
[14] NSF, “The Second Annual Report of the National Science Foundation, Fiscal Year 1952,” U.S. Government Printing Office., Washington, D.C., 1952.
[15] NSF, “NSF FY 2024 Budget Request to Congress,” 2023. Accessed: Feb. 08, 2024. [Online]. Available: https://nsf-gov-resources.nsf.gov/2023-08/NSF%20FY24%20CJ_Entire%20Rollup_web_%28ERRATA%20v4%29.pdf?VersionId=O1Um6rPm6xnLj80uA05Dm7IwxHUqScDO
[16] NSF, “The Sixth Annual Report of the National Science Foundation, Fiscal Year 1956,” U.S. Government Printing Office., Washington, D.C., 1956.
[17] NSF, “The Seventh Annual Report of the National Science Foundation, Fiscal Year 1957,” U.S. Government Printing Office., Washington, D.C., 1958.
[18] NSF, “The Eighth Annual Report of the National Science Foundation, Fiscal Year 1958,” U.S. Government Printing Office., Washington, D.C., 1959.
[19] JFK Library, “Address at the Anniversary Convocation of the National Academy of Sciences, 22 October 1963.” Accessed: Feb. 08, 2024. [Online]. Available: https://www.jfklibrary.org/asset-viewer/archives/jfkwha-233-003
[20] R. J. Bazell, “NSF: Is Applied Research at the Take Off Point?,” *Science*, vol. 172, no. 3990, pp. 1315–1317, 1971.
[21] NRC (National Research Council), *Priorities for Research Applicable to National Needs*. Washington, D.C.: National Academies Press, 1973, p. 20383. doi: 10.17226/20383.
[22] NSF, “CHIPS and Science.” Accessed: Feb. 08, 2024. [Online]. Available: https://new.nsf.gov/chips

[23] NSF, “About TIP - Directorate for Technology, Innovation and Partnerships (TIP) | NSF - National Science Foundation.” Accessed: Feb. 08, 2024. [Online]. Available: https://new.nsf.gov/tip/about-tip
[24] M. R. Roberts, “Realizing Societal Benefit from Academic Research: Analysis of the National Science Foundation’s Broader Impacts Criterion,” *Social Epistemology*, vol. 23, no. 3–4, pp. 199–219, Jul. 2009, doi: 10.1080/02691720903364035.
[25] NSF, “NSF in a Changing World.” Accessed: Feb. 01, 2024. [Online]. Available: https://www.nsf.gov/pubs/1995/nsf9524/contents.htm
[26] NSF, “Perspectives on Broader Impacts,” NSF, Washington, D.C, 2013. Accessed: Feb. 01, 2024. [Online]. Available: https://nsf-gov-resources.nsf.gov/2022-09/Broader_Impacts_0.pdf
[27] NSF, “Broader Impacts.” Accessed: Feb. 08, 2024. [Online]. Available: https://new.nsf.gov/funding/learn/broader-impacts
[28] D. Verdín, “Quantifying and Assessing Trends on the National Science Foundation’s Broader Impact Criterion,” *School of Engineering Education Graduate Student Series*, Jan. 2017, [Online]. Available: https://docs.lib.purdue.edu/enegs/71
[29] S. M. Watts, M. D. George, and D. J. Levey, “Achieving Broader Impacts in the National Science Foundation, Division of Environmental Biology,” *BioScience*, vol. 65, no. 4, pp. 397–407, Apr. 2015, doi: 10.1093/biosci/biv006.
[30] J. R. Kamenetzky, “Opportunities for impact: Statistical analysis of the National Science Foundation’s broader impacts criterion,” *Science and Public Policy*, vol. 40, no. 1, pp. 72–84, Feb. 2013, doi: 10.1093/scipol/scs059.
[31] B. Bozeman, “Public Value Science,” *Issues in Science and Technology*, vol. 36, no. 4, pp. 34–41, 2020.
[32] T. S. Woodson, E. Hoffmann, and S. Boutilier, “Evaluating the NSF broader impacts with the Inclusion-Immediacy Criterion: A retrospective analysis of nanotechnology grants,” *Technovation*, vol. 101, no. C, 2021, Accessed: Feb. 08, 2023. [Online]. Available: https://ideas.repec.org//a/eee/techno/v101y2021ics0166497220300821.html
[33] T. Woodson and S. Boutilier, “Impacts for whom? Assessing inequalities in NSF-funded broader impacts using the Inclusion-Immediacy Criterion,” *Science and Public Policy*, vol. 49, no. 2, pp. 168–178, Apr. 2022, doi: 10.1093/scipol/scab072.
[34] NSF, “NSF History - Nifty 50.” Accessed: Feb. 08, 2024. [Online]. Available: https://www.nsf.gov/about/history/nifty50/index.jsp
[35] NSF, “NSF Sensational 60,” The National Science Foundation, Arlington, VA, 2010. [Online]. Available: https://www.nsf.gov/about/history/sensational60.pdf
[36] NSF, “History Wall.” Accessed: Feb. 08, 2024. [Online]. Available: https://www.nsf.gov/about/history/history-wall.jsp
[37] N. Fuller, *NSF History Wall*. 2022.
[38] NSF, “CAD/CAM, Nifty 50.” Accessed: Feb. 08, 2024. [Online]. Available: https://www.nsf.gov/about/history/nifty50/cadcam.jsp
[39] G. Constable and B. Somerville, *A Century of Innovation: Twenty Engineering Achievements that Transformed our Lives*. Washington, DC: Joseph Henry Press, 2003. doi: 10.17226/10726.
[40] NASEM, *Extraordinary Engineering Impacts on Society: Proceedings of a Symposium*. Washington, D.C.: National Academies Press, 2023, p. 26847. doi: 10.17226/26847.

[41] NRC (National Research Council), *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure*. Washington, D.C.: National Academies Press, 1995, p. 4948. doi: 10.17226/4948.
[42] NASEM, *Continuing Innovation in Information Technology: Workshop Report*. Washington, D.C.: National Academies Press, 2016, p. 23393. doi: 10.17226/23393.
[43] NRC, *Information Technology Research, Innovation, and E-Government*. Washington, D.C.: National Academies Press, 2002, p. 10355. doi: 10.17226/10355.
[44] NRC, *Innovation in Information Technology*. Washington, D.C.: National Academies Press, 2003, p. 10795. doi: 10.17226/10795.
[45] NRC, *Assessing the Impacts of Changes in the Information Technology R&D Ecosystem: Retaining Leadership in an Increasingly Global Environment*. Washington, D.C.: National Academies Press, 2009, p. 12174. doi: 10.17226/12174.
[46] NRC, *Continuing Innovation in Information Technology*. Washington, D.C.: National Academies Press, 2012, p. 13427. doi: 10.17226/13427.
[47] NAE, "NAE Grand Challenges for Engineering," The National Academies Press, Washington, DC, 2008. Accessed: Feb. 07, 2023. [Online]. Available: https://nae.edu/187212/NAE-Grand-Challenges-for-Engineering
[48] NAE, "Grand Challenges - About the NAE Grand Challenges Scholars Program." Accessed: Feb. 08, 2024. [Online]. Available: https://engineeringchallenges.org/14384.aspx
[49] NSF, "NSF Award Search: Award # 0632026 - Grand Challenges for Engineering." Accessed: Mar. 19, 2024. [Online]. Available: https://www.nsf.gov/awardsearch/showAward?AWD_ID=0632026&HistoricalAwards=false
[50] NAE, "Grand Challenges - 14 Grand Challenges for Engineering." Accessed: Feb. 08, 2024. [Online]. Available: https://www.engineeringchallenges.org/challenges.aspx
[51] NAE, "Extraordinary Engineering Impacts on Society - YouTube." Accessed: Feb. 08, 2024. [Online]. Available: https://www.youtube.com/playlist?list=PLJ8uEbBRJZKeNwkEDUW-ymtEKNKeTYoEL
[52] *2 - John Anderson*, (Oct. 13, 2022). Accessed: Feb. 08, 2024. [Online Video]. Available: https://www.youtube.com/watch?v=hyA_JadWlQU
[53] *1 - Symposium introduction - Dan Arvizu*, (Oct. 13, 2022). Accessed: Feb. 08, 2024. [Online Video]. Available: https://www.youtube.com/watch?v=BZSnAcaJ1EQ
[54] *25 - Karen Lozano*, (Oct. 13, 2022). Accessed: Feb. 08, 2024. [Online Video]. Available: https://www.youtube.com/watch?v=dEDVi1hvp2o
[55] NAE, "Members: Professor Karen Lozano," NAE Website. Accessed: Feb. 08, 2024. [Online]. Available: https://nae.edu/290088/Professor-Karen-Lozano
[56] *16 - Paula Hammond*, (Oct. 13, 2022). Accessed: Feb. 08, 2024. [Online Video]. Available: https://www.youtube.com/watch?v=ybMiS8un2so
[57] NAE, "Members: Dr. Paula T. Hammond," NAE Website. Accessed: Feb. 08, 2024. [Online]. Available: https://nae.edu/165606/Dr-Paula-T-Hammond
[58] *33 - Rory A. Cooper*, (Oct. 12, 2022). Accessed: Feb. 08, 2024. [Online Video]. Available: https://www.youtube.com/watch?v=cU4YAtzgPcA
[59] G. Downey and K. Beddoes, *What is Global Engineering Education For? The Making of International Educators*, 1st edition. San Rafael, Calif. (1537 Fourth Street, San Rafael, CA 94901 USA): Morgan & Claypool Publishers, 2011.

[60] E. Blue, M. Levine, and D. Nieusma, “Engineering and War: Militarism, Ethics, Institutions, Alternatives,” *Synthesis Lectures on Engineers, Technology, and Society*, vol. 7, no. 3, pp. 1–121, Dec. 2013, doi: 10.2200/S00548ED1V01Y201311ETS020.
[61] G.H. Brundtland, “Report of the World Commission on Environment and Development: Our Common Future,” United Nations, Geneva, A/42/427, 1987. [Online]. Available: https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf
[62] D. Nieusma and X. Tang, “The Unbalanced Equation: Technical Opportunities and Social Barriers in the NAE Grand Challenges and Beyond,” *International Journal of Engineering, Social Justice, and Peace*, vol. 1, no. 2, Art. no. 2, Nov. 2012, doi: 10.24908/ijesjp.v1i2.4314.