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Evolution: Education and Outreach

BOOK REVIEW Open Access

How should scientists spread interest in, understanding of, and desire to practice, science more widely among the public?

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Abstract

This is a review of Bruce MacFadden's *Broader Impacts of Science on Society*. Here, MacFadden suggests how scientists should, and how the National Science Foundation tries to, spread interest in and understanding of science more widely, especially to underserved minorities, and make science-related professions more accessible to and attractive for these minorities.

Keywords: STEM (Science, Technology, Engineering, Mathematics), Workforce diversity, NSF's Broader Impacts requirement, Basic research, Social responsibility, Beauty

Book details

Broader Impacts of Science on Society, by Bruce J. MacFadden.

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Book review

This book, addressed primarily to fellow scientists, asks how to involve broader publics in science, and provides as context a history of the National Science Foundation (NSF) and its changing views on the relationship between science and society. It addresses the different ways the NSF has promoted interest in and understanding of science, and the desire, opportunity and ability to practice it, to wider publics. In recent years the NSF has focused especially on minorities grossly underrepresented in professions using science and mathematics, especially Hispanics and African-Americans. Today, the NSF's primary tool for arousing interest, understanding, and active participation in science is requiring NSF proposals—applications for NSF funding—to include a "Broader Impacts" section devoted to advancing these goals, which in theory weighs equally with scientific merit in the decision to fund. The author is a distinguished paleontologist, who has skillfully directed the Florida Museum of Natural History; created a website, Fossil Horses in Cyberspace, that still attracts many viewers after 23 years; and provided many high school teachers with research experience that enlivens their teaching. In short, he practices what he preaches. The reviewer is a retired evolutionary biologist who never needed NSF funding either to do research or win promotion. He entered science to better appreciate the beauty of nature, and has a lively sense of the importance of both the humanities and the sciences, in teaching people how to think, be responsible citizens, and appreciate the world's abundant beauty without ignoring its monstrous weight of injustice.

Two items essential to the book's argument must first be discussed. The first is the "concept" of STEM—Science, Technology, Engineering, Mathematics. Society needs them all, but they are very different. Mathematics is a form of ritualized play (sensu Huizinga 1950), analogous to poetry. "A mathematician, like a painter or

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poet, is a maker of patterns… The mathematician's patterns, like the painter's or the poet's, must be *beautiful*; the ideas, like the colours or the words, must fit together in a harmonious way" (Hardy 1967, pp. 84, 85). In mathematics, "concepts outside those contained in the axioms are defined with a view of permitting ingenious logical operations which appeal to our aesthetic sense both as operations and also in their results of great generality and simplicity" (Wigner 1960, p. 4). Yet forms of mathematics invented in ritualized play proved "unreasonably effective" as languages for various physical theories (Wigner 1960). Much basic research seeks to reveal new forms of order in nature and is motivated by the desire to better appreciate the beauty of the natural world: the construction of such theory is a form of art. Hutchinson (1953, p. 225) remarked "the statements of conceptual schemes [theories] of the inductive sciences are art forms and have to varying degrees a property dependent on their generality and coherence of structure… which is commonly called 'beauty'". Yet the science produced by those seeking to understand the order and beauty of some aspect of nature has continually yielded applications that became essential for the world's welfare. Technology and engineering are one bridge from science and mathematics to society whereby the findings of science are used for society's benefit. But science, like art, creates and reveals beauty. Science also shapes and transforms world-views, as when Copernicus, Galileo and Kepler taught us to see the earth, not as the center of the universe, but a planet of a rather peripheral star in a relatively peripheral galaxy (Koyré 1957).

The second item is a report Vannevar Bush wrote in 1945 for President Roosevelt, "Science, the Eternal Frontier," which largely shaped the goals and structure of the NSF when it was founded in 1950. If all of today's bureaucrats could think and write so clearly, the world would be a better place. Bush showed that progress in science was essential for national defense, public health and economic development. He accepted the paradox that supporting basic research, devoted to understanding the order and beauty of nature without thought of practical application, was the best way to maintain the flow of applications essential for human welfare. He wanted NSF to avoid controlling the directions of basic research and leave the management of science and scientists to universities and private research institutes. He wanted scientists to publish, and teach courses to graduate and undergraduate students, but otherwise left free to do research. Since science needs scientists, he wanted NSF to offer enough fellowships for graduate study that poverty (or race or gender) should be no barrier to those with the desire and ability to do science, and make intellectual ability the only ceiling. He did not want improvement in science education to injure study of the humanities, which he considered equally important to civilization.

MacFadden's first chapter is an excellent introduction to his book. He starts (p. 1) with the question he asks students taking his Broader Impacts class: Why do you want to be a scientist? Some want to understand the world, others want to benefit society and make the world a better place. He prefers the second answer as more socially responsible. He then reviews Bush's (1945) argument that science is essential for national defense, public health, and a prosperous economy offering a diversity of opportunities and occupations. Like Bush, he (p. 6) accepts Flexner's (1939) thesis that basic research, done without thought of application, is by far the best source of useful applications. MacFadden himself is a paleontologist, a science seemingly immune to applications. He observes (p. 7) that women and the more impoverished minorities are severely under-represented in science-related jobs—and that there are too few jobs for graduates in most science-related fields. He observes how the internet has facilitated exchange of information and multiplied cooperation among scientists of different nations. Finally, he notes that although most of the US public recognizes that science benefits society, they trust scientific findings on evolution and the human role in global warming far less than do peoples of other developed nations. This circumstance tempts some politicians to interfere more overtly in scientific issues, a phenomenon Bush (1945) sought to make impossible. Hence the book's major themes: how to increase the public's trust of, and sympathy for, science, and how to open science-related occupations more widely to women and impoverished minorities.

The second chapter is a history of the NSF, emphasizing the story of the Broader Impacts section required of all NSF proposals since 1997, and intended to weigh equally with scientific merit in the decision to fund. Despite MacFadden's (p. 24) protestations, this requirement was novel. NSF was founded to benefit society by supporting basic research to maintain the flow of applications useful to society. Moreover, engaging in research enabled professors to illustrate the joy of learning to students by personal example (Hutchinson 1953, p. 146). NSF also supported the material bases of research, ranging from special instruments like telescopes and electron microscopes to natural history museums, whose collections enable the study of evolutionary history (Simpson 1951), systematics (Mayr 1942) and biogeography (Simpson 1965). Museums also play a major role in education: Hutchinson (1979), p. 240 noticed "the extraordinary number of school children, many from the inner city, who may… have their first truly intellectual experience" visiting Yale University's Peabody Museum. From its start, NSF also tried to broaden access to science-related professions by offering research participation grants to science undergraduates and fellowships for graduate study in science. Until 1997, the NSF obeyed the injunctions of Flexner (1939) and Bush (1945) to judge proposals strictly by scientific promise and leave grantees free to do their science.

The Broader Impacts requirement evoked protests. By 1997, universities were leaving their faculty little time to think, so scientists complained of this new demand on their limited time. MacFadden shows this complaint as little sympathy as Pharaoh showed the enslaved Israelites' complaint of the new demand that they gather the straw needed to make their quota of bricks (Exodus 5: 15–18). On the other hand, as universities now depend on the overhead from NSF grants, the Broader Impacts requirement forces them to help scientists communicate to broader publics, an activity which they had previously ignored, and even hindered by their own "extracurricular" demands on faculty time. The Broader Impacts requirement was expanded and made more explicit in 2010 to include activities most scientists were poor at and unused to doing. Meanwhile, some congressmen are trying to have NSF favor more immediately relevant research (p. 28), a fate Bush (1945) labored to avoid.

Next come chapters advising young scientists on how to succeed. As competition for NSF funding is ferocious, NSF proposals should be innovative (his examples of innovation all concern styles of outreach). If possible, proposals should exploit unique opportunities, as did MacFadden's successful proposal to take advantage of the widening of the Panama Canal to search newly excavated areas for bones of terrestrial vertebrates living there twenty million years ago. This project also offered unique opportunities for effective outreach, which he skillfully exploited to the great benefit of many. Proposals, especially their Broader Impact sections, should embrace a variety of perspectives. Next, he recommends ways of using different media to communicate effectively with various publics. He rightly emphasizes that one should be able to explain the aims of one's work in < 60 s—the verbal equivalent of an abstract (p. 43). MacFadden (p. 56) rightly argues that communicating to broader publics makes one better at communicating to fellow scientists. He does not refer, however, to the great communicators of the past—Darwin (1881), Fabre (1989), Haldane (1927, 1985), Schrödinger (1944), not to mention Galileo—perhaps because he thinks (rightly?) that essays and books have become an ineffective form of outreach. A chapter on self-promotion inadvertently reveals how hostile the modern academic setting, which denies time to think and presses for immediate results, quickly, abundantly and favorably cited, is to genuine originality. Another chapter treats the duties of advisors, whom he rightly feels should try to help, not use, students (p. 68), and the advantages and pitfalls of collaborations.

He then returns to NSF with a chapter entitled "Strategic vs curiosity science." He admits that "NSF's agenda is to support basic research for its own sake" (p. 82). He contrasts curiosity science following the researcher's own interests with strategic science "that fits into a broader predefined research agenda" (p. 82). In fact, pure researchers pursue understanding, so they ask questions whose answers shed light on related questions they consider important. The truly original ask questions whose answers reveal previously unexpected links among a host of other questions. The essential difference between pure and applied (strategic) research in MacFadden's sense (p. 82, Box 7.1) is the word "predefined." NSF rightly supports some socially urgent strategic science, related to the processes and impacts of global warming (p. 83) and how to make economies sustainable (p. 90). NSF also supports initiatives that broaden the spectrum of questions scientists can answer, most notably the development of new modes of analyzing gigantic data sets (p. 88). Several of NSF's "Ten Big Ideas" (p. 92) are devoted to evoking ideas from scientists about how to enable them to tackle a wider variety of problems, and bring people of more diverse backgrounds into science.

MacFadden then returns to outreach and inclusion. From his museum experience, he urges us to know our audiences' abilities and interests. For example, in designing a children's museum, one must realize that evolution is a concept most children below a certain age cannot grasp (p. 95). He emphasizes informal audiences, who come to museums to enjoy the experience, and wishes to share this pleasure with people of impoverished minorities or backgrounds. He also discusses other ways to communicate—internet, social media, public speaking (not personal conversation!), press releases, radio, TV, and visiting museums via internet videos (p. 105).

NSF was always committed to equity (absence of bias). Until 1997, NSF acted as if equity would entrain diversity and inclusion. This view made much more sense in 1950, when social mobility and sense of community were far greater than in 1997, when economic changes had increased income inequality (Wilson 2019 pp. 188–190). Nowadays, achieving inclusion and social diversity in science requires more active work. To see why, consider the life of the blind MacArthur fellow Geerat Vermeij (pp. 117–8). He had a supportive family, and the Netherlands gave him a good education, but his parents had to move to the US to give him suitable career opportunities. There, his education and self-confidence enabled him to choose a satisfying career (Vermeij 1996). Nowadays, too many children lack both intact families and educational settings that instill knowledge and self-confidence. NSF suggests various ways one can choose to enhance diversity and inclusion, among them the very efficacious one of offering prisoners science education leading to a college degree (p. 109), and displays at rural fairs and "pop-up museums" at local festivals (p. 115) that may attract others to the possibility of a scientific career. I suspect this kind of outreach usually requires both experience and careful thought to be effective. Few except distinguished professors have time either for careful thought or the kind of training needed to achieve effectiveness, and even they must fight to defend this time.

It is desirable to attract people of different social and ethnic groups into science. How is this best done? Both MacFadden (p. 121) and I were attracted to studying evolution by gifted, committed, tenth-grade teachers. Vermeij (1996, pp. 3–7) was attracted by a kindly, gifted fourth-grade teacher. How can these experiences be made more common? One Broader Impacts approach is to involve teachers in one's research (pp. 127–30) which, rightly done, enables them to convey the joy of learning. This works best when, like MacFadden's Panama fossil dig, the work involves exotic animals or an exotic site. Fossil digging under a hot tropical sun, however, can be repulsive under someone less interested in and concerned for teachers than MacFadden. Others have brought teachers to Barro Colorado Island (BCI), Panama, and "let them loose." The teachers were well-chosen, intelligent and outgoing: BCI researchers all wanted to explain their projects—good training in speaking simply—and show these teachers what they loved about the forest. Teachers and researchers all benefitted, as MacFadden (p. 130) predicted. This happened, however, because the NSF grantee could find a school administrator both interested in the project and able to choose suitable teachers for it. MacFadden (pp. 136–49) describes ways scientists can help teachers—by giving classroom talks (which must fit into lesson plans), helping design lesson plans, and involving graduate students in various aspects of teaching. Presentations from someone the students can identify with enough to feel able to follow her example can be especially effective, as the gifted Colombian student Catalina Pimiento showed when she addressed largely Hispanic classes in California (p. 134).

MacFadden discusses higher education more briefly. He emphasizes the importance of community (or junior) colleges as bridges where high school graduates desiring a university education but lacking sufficient knowledge of self-confidence to succeed can remedy these deficiencies (p. 152). At first, the Broader Impacts requirement could be satisfied by including research results in courses or involving undergraduates in laboratory or field research. Universities are institutions of higher learning: as Hutchinson (1953), p. 147 remarks, there is no "antithesis between learning and research, because if the teacher is not learning himself, he cannot teach by example." In trying to "go beyond," might the NSF compromise the most vital aspect of Broader Impacts? On the other hand, academic jobs are scarce: the Broader Impacts course MacFadden teaches (p. 156) may open alternative careers to his students.

Once attracted to science, how are students turned into scientists? MacFadden's academic advisors displayed love of research, and taught him how to work independently and ask big questions (pp. 124–5). Indeed, the common feature of great advisors, as judged by the number of first-class scientists they produce, seems to be knowing how to encourage students. Academia is most neglectful of its postdoctoral fellows, a weakness which the NSF is addressing (pp. 131–2).

MacFadden then turns from recruiting and training scientists to interesting the public in things scientific. He states several goals (Box 13.1): interesting people in science, conveying understanding of science, showing how to reason scientifically and apply this to daily life, enlisting commitment to further help science (p. 161). He claims that Americans usually learn most of their science outside school, which I think is more true of the humanities. He sees museums as major centers of informal learning (pp. 164–7). He shows how museums can present evolution more realistically (MacFadden et al. 2012), and how museums are made more interesting by interactive or hands-on exhibits or "butterfly forests" with live butterflies (p. 167). He also mentions science centers, mobile and "pop-up" museums, displays at fairs, festivals, airports and railway stations (pp. 167–74), science sections in newspapers, and radio programs.

One way to interest the public in doing science is involving it in scientific projects. Many museums depend on volunteers to assist visitors, guide tours, help maintain buildings and grounds, and the like. Some volunteers help professionals collect fossils and prepare them for storage or display (pp. 181–4). Better schooling in doing science is provided by "citizen science," projects employing large numbers of non-professionals (pp. 184–92). The Audubon Society's Christmas Bird Counts (Audubon Society 2020), started in 1900 in hopes of replacing bird-hunting contests and now involving tens of thousands of volunteers each year, provides data used to track declines of common bird species and to learn how global warming is affecting bird distributions. Volunteer-operated camera-traps monitor wildlife abundance and species composition (Kays et al. 2016, McShea et al. 2015, Parsons et al. 2018). Such projects presumably employ many rural volunteers interested in animals but otherwise previously unconcerned with science. Citizen science is a form of outreach that benefits both scientists and volunteers.

MacFadden then revisits uses of the internet. It makes possible online courses for widely distributed participants (p. 195), building networks of amateurs and/or professionals with common interests (some using social media) for easier information exchange (pp. 196–201) and providing online equivalents of field trips or museum visits (pp. 204–5). It would be sad if experience of nature or museums were limited to the internet, but many people have limited mobility. Finally, the internet allows management and analysis of huge data sets (pp. 206–7). Big data sets requiring explanation by complex models only analyzable by large computers may, however, change the meaning of "understanding" in ways that amplify the split between science and humanities. Computerized statistical significance tests of hypotheses based on "big data" have misled people that found them too complex for intuitive understanding (Detto et al. 2019).

MacFadden next discusses how best to design an NSF application's Broader Impacts section, a topic on which NSF applicants sorely need advice (p. 214). Its design requires too much care to be left to the last minute (pp. 210–3). Broader Impacts clearly reduces money for scientific research, which MacFadden is unconcerned about (p. 214). Given this (in his view, necessary) requirement, MacFadden suggests several ways to fulfill it.

Advance research in ways that promote learning and training (p. 217), which NSF has implicitly favored since 1952.

Broaden participation of underrepresented groups (p. 218), always an NSF goal but not (except for avoiding bias) a duty of individual researchers before 1997.

Enhance infrastructure for research and education (p. 219). NSF has always supported the former. NSF has also financed projects to design courses for impoverished minorities, such as the basic biology course taught by Douglas Morrison at the University of Rutgers, Newark.

Communicating to broader publics to enhance their understanding of science (p. 220).

All these measures, when successful, would benefit society (pp. 221–2).

MacFadden finally considers what NSF requires of large projects, apparently his book's main concern. NSF requires that large projects such as MacFadden's Panama fossil dig, have management plans (p. 224). These plans must state project goals which can plausibly be fulfilled during the project's lifetime and whose degree of achievement can be measured quantitatively, so the project's success can be assessed objectively. The plan should include mechanisms for resolving disputes, and for improving it in the light of experience. It should include means for coping with risks such as the death or early departure of key project members. Mechanisms are needed for responding to obstacles revealed, or opportunities opened by, unexpected discoveries that affect how best to attain research goals, which in turn requires effective two-way communication between field workers, first-stage data compilers/analysts, and project directors and managers (pp. 226–9). The plan should show what activities originally enabled by the grant, such as research on collections it financed or a website whose development it supported, will continue after the grant ends (p. 230). NSF requires that really large projects, such as the cooperative project MacFadden organized to digitize several hundred million research specimens scattered over many museums, have project managers who must possess diverse skills (pp. 225–6). Since NSF invests so much in a large project, NSF wishes to evaluate both its progress and its eventual success in fulfilling its goals, themselves designed with a view to objective evaluation of their fulfilment (p. 236). Such grants are expected to pay for their own evaluator, who will be expensive but useful (p. 238). MacFadden lists sample metrics of success such as publications, increased museum attendance, improved performance of students whose teachers benefitted from Broader Impact schemes, and teachers' responses to surveys (p. 246). Evaluations of novel Broader Impacts schemes should be published, but to do so, Institutional Review Boards must have reviewed how the evaluators were to collect their data. These last two chapters reveal how science has changed from a joyous process of learning to a laborious, self-sacrificing enterprise confronted by a multitude of bureaucratic obstacles that select for social over scientific skill.

In his concluding chapter, MacFadden observes that ever more of NSF's funding goes to "big science" (p. 251). Big science demands collaboration, often over long distances (p. 252), which in turn presupposes contact with a diverse array of fellow scientists (networking, p. 252). The internet allows easy maintenance of contact within one's network and instant transmission, not only of manuscripts and PDFs but also 3D images of specimens and huge data sets (p. 253). He repeats that scientists must improve their effectiveness of communication to both their peers and broader publics (p. 254). This requires ability to see oneself in the place of those addressed (theory of mind), which is best learned in literature courses (Kidd and Castano 2013). Clearly, achieving Broader Impacts goals will benefit society: equalizing opportunity always does. But will the Broader Impacts program he advocates work?

Near his book's end, MacFadden returns to answers students gave to "Why be a scientist?" (pp. 255–6). Some answered, laudably, "to make the world a better place." Now he calls the others "inwardly focused" who want "to discover something important." Watson and Crick wanted, and achieved (Watson 1968), just that—to society's great benefit. Most pure researchers, however, focus on, indeed, are devoted to, their subject, not themselves. Like romantic poets sharing the joy of their love, most wish to share the beauty of their discovery, as do Fabre's (1989) *Souvenirs Entomologiques*, Wallace's (1878) *Tropical Nature*, Chapman's (1929) *My Tropical Air Castle* and Thorne's (1994) *Black Holes and Time Warps*.

Recalling these authors raises the question: what should scientists strive to convey? Stuffing brains with information won't do unless students are motivated to learn it. Hutchinson (1953), p. 227 supposes instead that "the essential thing we mean by love is that we are more anxious for the loved object to persist than for ourselves to do so" and concludes that "the purpose of inductive knowledge is to produce conceptual schemes that are found to have beauty and which, therefore, give a certain degree of lovableness to the universe which it did not have before". Hutchinson's logic recalls that of the French novelist Georges Bernanos's (1945), p. 42 remark that "faith, which requires that I love my neighbor, invites me to understand him… the most sure and loyal way of loving him." Scientists must convey both how we better appreciate the beauty of nature by understanding its underlying order, and the joy of discovering aspects of this order. Pure researchers can do this best; many would if given time for it and credit toward promotion for doing it well.

Appreciating the beauty of physical theories such as gravitation, quantum mechanics and relativity theory requires mathematical literacy. Most science-related professions also require the use of mathematics. Yet people at all economic levels divide into those who "get mathematics" and those who don't. Mathematical illiteracy prevents many humanists from understanding some of science's most beautiful achievements: it is perhaps our civilization's most serious flaw. It is also a brutal barrier to equal opportunity. MacFadden ignores this problem. George Polya's (1957) *How to Solve It*, which sold a million copies since it first appeared in 1945, suggested approaches to it. Polya (1957, p. v) remarked that if a mathematics teacher only "drills his students with routine operations, he kills their interest… But if he challenges the curiosity of his students by setting them problems proportionate to their knowledge and helps them to solve their problems by stimulating questions, he may give them a taste for, and some means of independent thinking." His book suggests how to do this. J. S. Bach's Anna Magdalena Bach notebooks use Polya's strategy: they start, not with routine exercises, but pieces that are a joy for beginners to play, and work up to pieces that would exercise a Gustav Leonhart. Polya (1977) shows how to use trigonometry to estimate distances to the moon and sun, the first steps to understanding the universe beyond our own planet. Polya (1954) shows the role of analogy and empirical methods of hypothesis testing in mathematics, revealing surprising aspects of the unity of knowledge. First-year calculus courses taught by graduate students without teaching experience turn many off mathematics. Grants for devising experimental calculus courses for humanities students should thus be available for tenured professors inside and outside mathematics departments.

MacFadden's concern for Broader Impacts is partly driven by many Americans' refusal to accept scientific findings on evolution, natural selection, and the human role in global warming (pp. 12–14). This refusal probably reflects the dissolving sense of community in the US (cf Wilson 2019, pp. 187–192). Many of the divisive features of 1940s French politics—widespread indifference to truth vs falsehood, allowing one's party to think and judge in one's place, so that one is revolted by injustice and atrocities only when the party commands (Bernanos 1955, pp. 116, 118)—are resurfacing in the US. Wilson's (2007) excellent introduction to evolutionary theory is based on a course that overcomes these divisions, being equally successful with students of all political stripes and degrees of religious belief (Wilson 2007, pp. 7–9). He does this by his desire to share the joy his subject gives him, his emphasis on how social cooperation and mutualism among species shape evolution, and how much of human behavior evolutionary thinking can explain. Winning acceptance of the human role in global warming will be far harder. Not only does arresting global warming require uprooting too many ingrained habits: given the ineffectiveness of public transport in the US, arresting warming would impose gross hardship on many. Halting global warming will require a strong sense of community. Too many megabusinesses, moreover, feel threatened by an honest reckoning with global warming and spend huge sums to elect politicians who share their fears. Humanists like Nussbaum (2015) are probably best fitted to find ways to rebuild the sense of community in the US.

Ultimately, the Broader Impacts program seeks to equalize opportunity, largely by arousing interest in science and desire to practice it among people of all social backgrounds and economic levels. MacFadden finds Broader Impacts so urgent that, as his book progresses, he slowly loses sympathy with basic researchers, ending by speaking as if basic researchers have had it too easy and should be made to face the real world. Basic research without thought of application, however, is the surest source of applications benefiting society (Flexner 1939, Bush 1945). For both spectators and basic researchers, a primary attraction of basic research is the beauty it reveals. Yet MacFadden has written a book on how to stir interest in science without mentioning beauty! His book's other central problem is its lack of interest in how to take advantage of what scientists like doing to advance Broader Impacts, and which of that program's goals are better fulfilled by people more specifically trained for the tasks involved.

For all my criticisms, I think it urgent for educated people (not only scientists), to read this book. Equalizing opportunity is an essential aspect of rebuilding a sense of community, and in society's present state equalizing opportunity will not be easy.

Abbreviations

NSF: National science foundation; STEM: Science, technology, engineering, mathematics.

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