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Grand Challenges in US Science Policy Attempt Policy Innovation

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Abstract

This paper investigates the historical development of the Grand Challenges concept in US science policy. The concept originated in advocacy for funding for high performance computing and was enshrined in the High Performance Computing Act of 1991. The Bill & Melinda Gates Foundation's Grand Challenges in Global Health program marked a second milestone in the application of the concept to US science funding. The National Academy of Engineering's *Grand Challenges in Engineering* followed in 2008. Most recently the White House has pursued programs under the Grand Challenges rubric. The history of these varied initiatives spanning 40 years is examined here to identify core elements and continuity as well as to explore the relationship between innovation and tradition in U.S. science policy.

Keywords

Grand challenges; science policy; HPCC; global health; engineering; OSTP

1. Introduction

Talk of grand challenges has become commonplace in research policy in recent years. This is especially true in Europe after the use of "grand challenge" in the title of a key document describing the 8th Framework program and the renaming of that program's thematic priorities as societal challenges. Like a meme, the term appears in ever more places, applied to an ever greater number of projects without much critical thought in evidence. Analysts pondering the meme have arrived at varied interpretations. To some it is a buzzword and a passing fad (Rip, 2014). Others have been commissioned to determine what, exactly, are grand challenges (Kellerud et al., 2013; Leijten et al., 2012). Some speculate that the concept might be a harbinger of a fundamental transformation (Kuhlmann & Rip, 2014).

In Europe we may see an emerging sense of challenge oriented policy, often associated with the term "societal challenges". Such policy addresses the biggest issues of our time - climate change/energy, aging society, security, etc. It is policy that goes beyond national governments, requiring international cooperation, as well as policy that goes beyond research and innovation though both will likely be involved in any solutions. It is policy that probably entails transformation not only of research and society but also of policymaking itself (Kuhlmann & Rip, 2014). It may have a Europe-specific connotation of areas that are under the control of national governments, not the EU, but in which national governments will take direction from the EU or at least the Commission seeks influence (Leijten et al., 2012, p. 7).

European analyses of grand challenge policymaking are international in scope, and reference developments in the United States, often concluding that American use of the concept is less open ended and more focused on technology development (Kellerud et al., 2013; Leijten et al., 2012). US analysts of research policy have interpreted grand challenges in terms of their prior interests - mission oriented research, prizes, or the green revolution, (Mowery, 2012, Murray 2012; Wright 2012). In contrast, this paper seeks to examine grand challenges in US science policy in their own terms. This is not a comparison or reconciliation of US and European use of the term. Nor does it limit discussion to that which makes sense when viewed from existing frameworks. Historical examples of important policy initiatives framed as grand challenges are described. Common elements are sought in an effort to develop a definition of the concept as used in the United States. After this, the relationship between the grand challenge framing and the older framing of research as basic and applied is discussed. The paper argues that grand challenges have signaled attempts at innovation in research policy and examining them in this light illustrates the difficulty of changing existing frameworks

The paper is organized as follows. Each historical and contemporary example is discussed in turn: advocacy for funding for high performance computing by Kenneth G. Wilson; the Bill & Melinda Gates Foundation's Grand Challenges in Global Health program; the National Academy of Engineering's *Grand Challenges in Engineering*; the DARPA grand challenge competition, and recent White House initiatives. The efforts seem to share a sense of innovativeness, use of aspirational pedigrees and a definition. More or less common elements that might constitute a definition are found to be: combining the intellectual and practical, a desire to energize a community, ambitious scale, requiring interdisciplinary research, specification by a committee with a public call for suggestions, a request for resources and feasibility. Finally, grand challenges are discussed in terms of applied research to illustrate the difficulty of innovating policy mechanisms.

2. Origins

The use of the term "Grand Challenges" in science policy originated with Kenneth G. Wilson, a Nobel Laureate physicist who received his award for work on phase transitions in materials using supercomputer simulations. Described by Cornell as a "supercomputing visionary" he established a supercomputing center in 1985 called the "Cornell Theory Center."[i] In the early 1980s he was a prominent advocate for very large scale computers in theoretical physics. At the time, the idea of funding supercomputers as tools for theoretical physics faced opposition from eminent scientists. They objected to this newfangled, and therefore illegitimate, way of doing science and doubted it could add anything of value to the field. Wilson's advocacy work included writing papers and giving speeches in which he articulated the obstacles he faced in arguing for supercomputer funding.

Wilson's first documented contribution is found in an appendix to an early report to the National Science Foundation (NSF) and Department of Defense (DOD) on the use of large scale computing in science and engineering in which he said:

> *None of the committees I have served on including this workshop, have solved the problem of documenting the importance of computing support for theorists. Members bring lists of needs within their fields, but these lists seldom provide any overview of the importance of the needs. There must be a more ongoing effort to collect data establishing the scientific importance of theorists' computing needs, especially given the skepticism of many eminent scientists towards large scale computing. (Lax, 1982, Aii-20)*

At this point Wilson believes the problem is a lack of data, that is given enough examples of how supercomputing can contribute, his skeptical colleagues will be convinced by the evidence.

By 1984, Wilson was deep into long term advocacy for the US to adopt a coordinated, multi-faceted approach to large scale computing (see for example his testimony before Congress, Wilson, 1983). He described three years of visits, speeches and panels in a paper entitled: Science, Industry and the New Japanese Challenge (Wilson, 1984, p. 7). At the time, the success of Japanese companies had focused attention on their management practices. There were several books published around 1980 with "Japanese Challenge" in the title. So when the Japanese government announced a program to develop supercomputers for scientific and engineering use, it garnered publicity in the US, to which Wilson responded in this paper with his vision of the future. He advocated for things that have come to pass such as NSF support for the launch of the Internet; things that ended up in Grand Challenge lists – quantum chromodynamics - and things that remain on the most recent Obama administration list of Grand Challenges – computer aided instruction.

In this paper, Wilson also described six obstacles to his vision that he sought to overcome in his advocacy:

1. the difficulty his theoretical colleagues at Cornell have in accepting his vision (p. 11),
2. leading senior scientists fighting hard for basic research funding who view theoretical computing as unnecessary and a potentially disastrous drain on research budgets (p. 13),
3. the need for a practical understanding by senior management of the results to be expected from the scientific/engineering computing community (p. 16),
4. the need for much bolder planning on the part of universities (p. 17),
5. agencies and programs that prefer mission or discipline-oriented supercomputer programs (p. 17), and
6. "getting glared at by every other member of the committee" and so accepting an unsatisfactory solution such as a one-time appropriation rather than a permanent budget designated for scientific computing (p. 18).

We get a sense even today of Wilson's persistence and determination in refusing to accept as inevitable either existing institutional practices or perceptions. No doubt his recent Nobel Prize, with its accompanying ascendance into the most elite category of scientist, helped boost his confidence in his judgment and increased the persuasiveness of his arguments with others. Perhaps the "Japanese challenge" term, which had currency at the time, suggested to him "grand challenge." By 1987, Wilson was using "grand challenges" in the title of a talk in which he said:

> *The challenge is to move from the present situation, where there is plenty of research going on, to achieve the really spectacular discoveries which have not been made yet: the kind of discoveries that would make you run to the first colloquium on the subject, the way I used to run to the colloquia on pulsars when they were first discovered. (Wilson, 1988, p. 162)*

In this talk Wilson named two challenges - weather forecasting and electronic structure - and described them in depth. Wilson recognized here that the task of persuasion involves an emotional component, that there is a need to generate a sense of excitement, in addition to providing evidence and having authority.

Shortly afterwards, in 1989, he articulated the rationale for the use of the term "Grand Challenges" explicitly. Wilson again mentions the need for excitement as a component of efforts to win support and the difficulty of generating it in computing. He mentions pulsars again, as well as established disciplines like astronomy, materials science and molecular biology in which it is easier to generate that excitement. He goes on to write:

> *Unsupported promises of major breakthroughs have to be avoided because past experience has been that supercomputers are more difficult to achieve success with than initial expectations. At the other extreme, however, reference only to past or current successfully completed supercomputer projects provides too weak a case for the future. . . . .*

I propose an alternative approach. The major future opportunities for benefits of supercomputers to basic research should be identified without the existing compromises, but presented as challenges to be overcome with the many obstacles to success clearly explained. . . . . Furthermore, a few key areas with both extreme difficulties and extraordinary rewards for success should be labeled as the "Grand Challenges of Computational Science". (Wilson, 1989, p. 173)

By this point, Wilson has discarded the gathering of evidence because it has proven unequal to the task. Current achievements are so limited by current hardware that they cannot possibly justify the large amount of funding needed to overcome those very limits. A standard alternative approach in such situations is to make big promises. He wants to avoid that as well because disappointment will surely follow. He is presumably playing the long game and would not want large funding, once achieved, to be jeopardized shortly thereafter due to failure to deliver on initial promises.

One can imagine how the Grand Challenges formulation offered responses to each of the obstacles Wilson faced in advocating for large scale funding for computing in research. With the memory of the discovery of pulsars, Wilson recognized the need for an element of excitement in his vision. An exciting vision would be a more persuasive vision, and perhaps increase the chance that his fellow theoreticians would come to share the vision. The intent to open vast new domains previously inaccessible might appeal to those fighting Wilson to preserve funding for basic research. The benefits to be had by solving the big challenges Wilson proposed can be explained in terms understandable to non-specialists such as senior management, whose backing was required. The invitation to be “grand” suggests that boldness is required, a characteristic Wilson thought universities were singularly lacking. Solving the challenges requires interdisciplinary work, Wilson’s principal recommendation was the formation of an interdisciplinary community, providing a way out of the standard disciplinary or mission focus holding the field back. And to those suggesting Wilson compromise, presumably Wilson would dare anyone to suggest compromising on a Grand Challenge.

Wilson’s advocacy was ultimately successful. The work of Wilson, and many others, laid the foundation for the US entry into what was called at the time high performance computing.

3. Grand Challenges in high performance computing

Wilson's Grand Challenges formulation entered US Federal science policy discourse in the High Performance Computing & Communications (HPCC) program developed over the course of the 1980s. The HPCC realized Wilson's vision. The policy documents that established the HPCC strategy always included a list of high complexity problems in several disciplines that required computational power not yet available as well as sharing of computing resources across geographical areas due to the large collaborations that were envisioned to address these problems. The first such list of high complexity problems was included in the Lax Report of 1982 in which the need for high performance computing for American academics was first articulated.

The phrase "Grand Challenges" was associated with these lists of problems in a policy document around the time of Wilson's Cornell talk. In 1987 the Federal Coordinating Council for Science, Engineering and Technology (FCCSET) published "A Research and Development Strategy for High Performance Computing", which outlined what was to become the HPCC program (OSTP, 1991). The strategy/program had four components[ii] "grand challenges" were used to explain the software component and five fundamental problems were listed.[iii]

The HPCC program fully materialized with the passage of the High Performance Computing act in 1991 (Senator Gore sponsored the bill) associated with the publication by the White House Office of Science and Technology Policy (OSTP) of an addendum to the President's budget that elevated grand challenges from obscurity in the software section to the title. Chapter 4 described a list of 10 grand challenges (explicitly not comprehensive): forecasting severe weather, cancer genes, predicting new superconductors, air pollution, aerospace vehicle design, energy conservation and turbulent combustion, microsystems design and packaging, biosphere, high speed networks, and education using networks.

The High-Performance Computing Act incorporated a definition of Grand Challenges into the US legal code:

> *'Grand Challenge' means a fundamental problem in science or engineering, with broad economic and scientific impact, whose solution will require the application of high-performance computing resources and multidisciplinary teams of researchers (15 U.S. Code Chapter 81 - High-Performance Computing § 5503)*

In policy for high performance computing around 1990, grand challenges signaled lists of very difficult intellectual problems in science or engineering which would benefit from a multidisciplinary approach involving computing at a large scale. From the perspective of computing, this would be an application, and in Wilson's phrasing these would be the "Grand Challenges of Computational Science". Wilson also linked his new policy term to a desire to excite and energize a community.

4. Bill & Melinda Gates Foundation Grand Challenges in Global Health (BMGF GCGH)

In 2000, the Bill & Melinda Gates Foundation, recently founded though the merger of two predecessor foundations, joined with others to work on the UN's Millennium Development Goals which were announced that year. The Foundation provided grants for health care providers, for example delivering vaccines or providing education about and treatment for schistosomiasis. There were non-profits supporting biomedical research, but the Gates Foundation was not yet prominent among them.

This changed in 2003 when the Foundation announced their intent to identify research areas with the greatest promise for saving and improving lives in the developing world; to fund novel, interdisciplinary approaches among researchers seeking solutions; and to get the richworld scientific community to apply its experience to pivotal health questions of the developing world. Bill Gates announced his plans at Davos in 2003 and followed up with an article in the *Wall Street Journal* (Gates, 2003). The Gates Foundation then issued a request for ideas to the scientific community and convened a board of 20 scientists and public health experts from 13 countries, including several from the developing world and the director and ex-director of the National Institutes of Health (NIH). The board published the results of their deliberations in an article in *Science* (Varmus et al., 2003). Gates had originally pledged $200 million, but interest was so strong that the budget was increased. $458 million was awarded in what became the first round of a program that has exceeded 13 rounds of proposals and awards.

Gates named his initiative Grand Challenges in Global Health (GCGH). This was unusual. The conventional name would have been Gates Overseas Infectious Disease Program and the conventional mechanism would have been to announce the area of interest and solicit proposals. The Wellcome Trust for example had been funding research on malaria in laboratories in Southeast Asia since the 1970s under its Major Overseas Programmes. Grand Challenges sounds more Davos-worthy and perhaps justified the attentions of the *Wall Street Journal* in a way that an overseas infections disease program would not have, but the raised expectations can have a downside.

After 10 years, one fifth of the original Gates projects were moving towards fruition, for example a plan to make mosquitoes immune to the virus that causes dengue fever, a drink containing bacteria that kill cholera-causing bacteria, and a much cheaper machine to stop the collapse of lungs in premature babies (Economist, 2014). These would be solid successes for a Gates Overseas Infectious Disease Program and may justify the original investment. For a Grand Challenges in Global Health however, these successes invite disappointment, not being blockbusters nor particularly grand (Economist, 2014).

“Global health” was an overly broad claim for an initiative addressing only the infectious disease component of health in non-Western nations, thus two further groups on global health were convened outside the Gates umbrella. The most cited of these post-GCGH papers[iv] was published in 2007 in *Nature* and entitled "Grand challenges in chronic non-communicable diseases" (Daar et al. 2007). Its two lead authors, Daar and Singer were on the GCGH board and were coauthors on the 2003 GCGH *Science* article. A second initiative was published in *Nature* in 2011 and entitled “Grand challenges in global mental health” (Collins et al. 2011).

The unusual name may have had a direct connection to the earlier efforts. When his foundation was considering entering research, Bill Gates likely discussed his plans with the person who advised him when Microsoft entered research, Gordon Bell. As assistant director of NSF’s computing directorate, Bell chaired one of the three subcommittees that wrote the 1987 report which first used the term "Grand Challenges." During the early 1990s Bell advised Microsoft on setting up a research unit and in 1995 Bell joined Microsoft Research.

The Gates effort is similar to the earlier high performance computing effort in more than its name. Both aimed to identify intellectual problems with promise of solving practical problems. Gates’ combined intellectual/practical aspect mirrors the combined scientific research/computing character of the computing grand challenges. Like the earlier grand challenges, Gates explicitly called for interdisciplinary work, and wanted to energize a community and work on a large scale. The term was also introduced in rhetoric concerning research funding. Finally, the board of 20 scientists published in *Science* a 14 point to do list, mirroring the list approach begun by Wilson.

There were also innovations in the Gates approach. New was the systematic process used to devise the list in which a committee of 20 scientists consulted with the broader community and with the public, though this mirrored the standard National Academies approach, used in several grand challenges documents, see below. The Foundation had worked on another to do list, the United Nation's (UN) Millennium Development Goals, which may have served to demonstrate the power of to do lists with big names. The UN goals are expressed in active form, for example: "Goal 1: Eradicate extreme poverty and hunger." This contrasts with the complex nouns that served as grand challenges within the computing community, for example "calculations to understand the fundamental nature of matter." Mirroring the Millennium Goals, the GCGH differs from previous challenge lists in taking the active form:

- Goal 1: Improve childhood vaccines
    - Grand Challenge 1: Create effective single-dose vaccines
    - Grand Challenge 2: Prepare vaccines that do not require refrigeration
    - Grand Challenge 3: Develop needle-free vaccine delivery systems

Curiously, in announcing the GCGH, Gates did not mention Wilson as originator of the grand challenge concept nor high performance computing as a precedent. Instead, the *Wall Street Journal* article began by invoking what was framed as "another worldwide call to action," David Hilbert's 1900 list of 23 unsolved mathematical problems (Gates, 2003; Hilbert, 1902). In that Hilbert made a list - of problems - there is a similarity. But the similarity ends there. Hilbert's context was millennial, he mentions the turn of the century as an appropriate time to reflect on the future. Hilbert's list is disciplinary, not interdisciplinary; in fact he was concerned with the unity of mathematics. The problems are purely intellectual,[v] research funding was irrelevant, there was no scale -individual investigators were the focus – and Hilbert was reassuring rather than energizing, noting that because mathematics had many unsolved problems, it had a future. Hilbert's list is closer in kind to the academic papers with grand challenges in their titles that proliferated in the computer science literature after the HPCC and more broadly across all fields post GCGH. Closer to the mark was Gates' mention of the human genome mapping as "a model of a successful international, interdisciplinary" effort (Gates, 2003). Though as a big science effort, that too really was different. Perhaps the closest precedent was the UN's Millennium Development Goals which were not mentioned.

The Gates Foundation entered research funding in response to its perception that postwar government institutions (i.e. NIH) had failed to address serious gaps in knowledge relevant to the diseases of the poor in developing countries. The Gates Foundation was a new actor in research policy, addressing a perceived failure of established research funders. Gates wrote: "Every year $70 billion is spent on medical research and development, yet only 10% is devoted to the diseases that cause 90% of the global health burden" (Gates, 2003). Gates framed the problem in a way that transcends national boundaries. National governments allocate that $70 billion in medical R&D funding in accordance with national priorities. But viewed from a global perspective, the disease burden is in a different place than are the constituents of national governments with substantial research funding. Gates introduced this global perspective into an area of policy that had hitherto had clear geographic scope. To Maarten Hajer this would exemplify the increasingly common situation in which "solutions for pressing problems transgress the sovereignty of specific polities." (Hajer, 2003, p. 175).

This intervention in science policy was successful. The agenda of the NIH altered in response to the GCGH, with the NIH subsequently allocating more resources to research on developing country infectious diseases (Kirstin & Matthews, 2008). In addition, the Canadian, Brazilian and Indian governments have each launched their own grand challenge grants programs in partnership with the Bill & Melinda Gates Foundation. Thus "grand challenges" (accompanied by large amounts of money) functioned here to help a nontraditional actor, a non-profit, enter science policy and shift the priorities of traditional actors and institutions.

5. Grand Challenges for Engineering

The National Academies Press has published more than 100 reports that mention grand challenges. In the early 1990s computer science reports extensively referenced the then recent grand challenges in the HPCC initiative. This pattern was broken in 1998 with the appearance of a report entitled: *Visionary Manufacturing Challenges for 2020* with a chapter entitled "Grand Challenges for Manufacturing". 2001 saw the appearance of *Grand Challenges in Environmental Sciences*, a report much referenced in succeeding reports. The NSF was a sponsor of all of these reports, and sole sponsor of some.

One of the NSF sponsored reports was the 2008 National Academy of Engineering (NAE) *Grand Challenges for Engineering*. This report was produced by a "blue-ribbon" committee of "leading thinkers from such areas as technology, science, business, politics, and entertainment" (NSF, 2006). "Key, and unique, to this project [was] a focus on public outreach" (NSF, 2006). The effort aimed to improve public understanding of engineering; to excite young people about an engineering career; and to uncover examples of engineering research opportunities. Despite the high powered group and the directive to collaborate with "one or more major media outlets" (NSF, 2006), the report landed with "a dull thud" in the words of the NAE president Charles Vest (Kaplan-Leiserson, 2011). There was essentially no press coverage.

The engineering report's main line of development may have gone nowhere, however, there have been spinoffs. Ray Kurzweil, then CEO of Kurzweil Technologies, was a member of the engineering committee. In 2009, he founded Singularity University whose mission statement and indeed website is liberally sprinkled with the term "grand challenges."[vi]

Also in 2009 Duke University's Pratt School of Engineering commissioned a public survey of attitudes towards engineering and engineering challenges. The survey asked whether engineering issues and problems were more interesting and important than those of medicine, business and law. 40% thought they were. After hearing descriptions of five of the engineering grand challenges, that proportion increased to 54%. "Demographic groups exhibiting the greatest increases include women without a four-year college degree (+24 points), African Americans (+22 points), and 18- to 34-year-olds (+21 points)" (Hart, 2009, p.3). These are key demographic groups for engineering degree programs. Over a series of workshops endorsed by the NAE support was gathered, and in 2015, deans of 122 U.S. engineering programs delivered to President Obama commitments to enhance their undergraduate degrees with grand challenge programs offering five co-curricular components: GC related research or design projects; client projects; entrepreneurship and innovation experience; global and cross-cultural perspectives; and problem-based community projects, i.e. service-learning. The press release explicitly linked this effort with the Engineering Grand Challenges and with the White House 21st Century Grand Challenges, see below (NAE, 2015).

The engineering effort was similar to Gates' in proposing a list of 14 grand challenges devised by a committee of eminent worthies consulting more broadly, including with the public. Another point of similarity was the explicit motivation of exciting people to engage with engineering. However, the engineers are silent on much else: the intellectual-practical nature of the problems, scale and interdiscipliarity. "Unprecedented levels of public funding" will be required to meet the challenges, yet funding advocacy has not been a feature of the report follow-on.

6. Competitions

There is another line of grand challenge development concerned with competitions. The original grand challenge is a rowing competition for men's eights in Oxford. Dating from 1839, the Grand Challenge Cup is the oldest and best-known even at the annual Henley Royal Regatta on the River Thames. Kenneth G Wilson spent a year in Oxford as a teenager (Nobel Foundation, 1991) and so likely knew about this race.

At about the same time as the GCGH started, DARPA became the first government agency to apply the term grand challenge to a competition – a long distance trial for driverless cars. The first DARPA Grand Challenge was announced in 2002 and took place in 2004. Nobody finished. There was a winner in 2005 and the competition was held three times before its name was changed to the robotics challenge in 2012 and then the FANG challenge in 2013. The DARPA Grand Challenge followed the first big innovation competition of the modern era, the private Ansari X PRIZE announced in 1996 and won in 2004 by Spaceship One. Wikipedia notes that the DARPA Grand Challenge was the first effort in autonomous cars not using traditional mechanisms of corporate development or academic research grants.

The mechanism of challenge competitions as an alternative tool to encourage innovation has developed greatly under the Obama administration. On his first day in office, President Obama issued a memorandum for Heads of Executive Departments and Agencies entitled Transparency and Open Government. In the memo, the President committed his administration to innovation in government seeking, among other things, to offer Americans increased opportunities to participate in policymaking and to use innovative tools to collaborate with those outside government (Obama, 2009). Implementation followed with OMB issuing guidance to agencies on using challenges and prizes (as well as citizen science) as innovative policy tools in addition to the traditional tools of taxes, regulations, contracts, research grants etc. (Zients, 2010; Weinstein, 2010; NEC & OSTP, 2015). The COMPETES act reauthorization of 2010 granted agencies legal authority to conduct prize competitions, and much work has gone into developing agency capacity as well as building the challenge.gov platform. As of 2015, 440 Federal challenges have been conducted by more than 80 agencies with over $150 million in prizes through challenge.gov (NEC & OSTP, 2015).

7. The White House manifesto

The association of the Obama White House Office of Science and Technology policy with Grand Challenges has evolved. At first the OSTP was somewhat hesitant to engage with the concept. In its first *A Strategy for American Innovation*, published in 2009, the phrase grand challenges occurs three times in scare quotes and once without. The final section and subsections are entitled:

Catalyze Breakthroughs for National Priorities

- *Unleash a clean energy revolution*
- *Support advanced vehicle technologies*
- *Drive innovations in health care technology*
- *Harness Science and Technology to Address the "Grand Challenges" of the 21st Century.* (NEC & OSTP, pp. 19-22)

Under the grand challenges heading, eight important, though somewhat miscellaneous, fairly specific and so not obviously grand, challenges were articulated in the noun form, for example "a light-weight vest for soldiers and police officers that can stop an armor-piercing bullet." This is especially odd since this list follows three much grander challenges phrased much more forcefully. The Strategy for American Innovation was updated in 2011 in a document that uses grand challenges once in passing, without scare quotes.

The OSTP's hesitancy towards "grand challenges" shifted to full engagement in 2012 with the hiring of an Assistant Director for Grand Challenges, Christin Dorgelo, formerly the XPRIZE Foundation manager of active competitions. White House and OSTP announcements of research programs, incentive prizes and agency initiatives thereafter elaborated an argument for the importance of grand challenges. Tom Kalil's name is associated with much of this activity. Kalil came to OSTP from Berkeley where he initiated multi-disciplinary initiatives defined both in the traditional manner by the research areas being brought together and in the innovative framing of societal challenges in energy, water and poverty. He also worked in global health at the Clinton Foundation and so must have encountered the Gates GCGH.

In April 2012 in a speech at the Information Technology and Innovation Foundation, Kalil explained grand challenges. This speech is the only document devoted solely to describing the theory of grand challenges. Almost every other document substantively engaging grand challenges contains a to-do list. Kalil defined Grand Challenges as "ambitious yet achievable goals that capture the public's imagination and that require innovation and breakthroughs in science and technology to achieve" (Kalil, 2012, p. 1). Grand Challenges are a central mechanism in the President's Innovation Strategy. The precursors mentioned are President Kennedy's initiative to land a man on the moon, the Human Genome Project and, somewhat unconventionally, Wikipedia.[vii] Five attributes were listed:

1. potential for major impact in domains such as health, energy, sustainability, education, economic opportunity, national security, or human exploration
2. ambitious but achievable,
3. compelling enough to capture the public imagination,
4. measurable targets for success and completion
5. can help drive and harness innovation and advances in science and technology.

President Obama calls for an "all hands on deck" approach to the identification and pursuit of Grand Challenges involving government agencies, philanthropists, foundations, research universities, companies, investors, and "America's storytellers" including media companies. The administration encourages us "to imagine a world in which more individuals and institutions are involved in pursuing or supporting a Grand Challenge and a world in which these challenges play a more prominent role in our culture and in our public discourse" (Kalil, 2012, p.5)

In comparison with previous initiatives, there is more emphasis on the excitement aspect. Wilson explicitly recognized the need for the emotional engagement of excitement to enhance the persuasiveness of his effort. The charge to the NAE from NSF listed excitement as goal number 2 in aid of recruiting young people to the engineering career (NSF, 2006). Gates too mentioned recruiting new scientific talent as well as increasing public attention in order to increase public investment (Gates, 2003). The White House defining grand challenges as that which "captures the public's imagination," as "compelling and intrinsically motivating," and calling for "all hands on deck" efforts, is clearly intended to realize the vision of participatory and collaborative government laid out in the Transparency and Open Government memo (Obama, 2009). The broad group of collaborators sought includes media companies perhaps the only time in US science policy that media companies are positioned as integral to the effort.

On April 2, 2013, President Obama announced his 21st Century Grand Challenges initiative with which several agency programs are associated.[viii] NASA's Asteroid Grand Challenge aims to find all asteroid threats to human populations and decide what to do about them. The initial framing aligns well with the manifesto. It was announced at an asteroid initiative industry and partner event, is a large-scale effort that will use multi-disciplinary collaborations and a variety of partnerships with other government agencies, international partners, industry, academia, and citizen scientists. "This Grand Challenge is focused on detecting and characterizing asteroids and learning how to deal with potential threats. We will also harness public engagement, open innovation and citizen science to help solve this global problem." (NASA, 2013). The influence of the grand challenge manifesto may have been to encourage the agency to address a big problem and see its work as setting up the question, recruiting partners and using the latest methods (citizen science, public input through the RFI) to address the problem. This differs from the traditional policy mechanism, an RFP requesting proposals from university and government scientists to perform research on the problem. The agency juxtaposed the grand challenge against its traditional effort in this area, which is a mission to redirect an asteroid and send humans to study it. The grand challenge agenda has produced several other programs: the cross agency BRAIN initiative to map the human brain, the Sunshot solar energy program of the Department of Energy (echoing the "moonshot" historical touchstone) and several grand challenges at the State Department. The NASA, DoE and State Department programs have used prize competitions.

In October 2015 *A Strategy for American Innovation* was updated for a third time (hereafter *Strategy* 2015). In this version, grand challenges appears 15 times. The section entitled *Catalyzing Breakthroughs for National Priorities* lists 11 action items, the first of which is: *Tackling Grand Challenges*. The grand challenges section offers a vision:

> *As President Kennedy once observed, "By defining our goal more clearly, by making it seem more manageable and less remote, we can help all peoples to see it, to draw hope from it, and to move irresistibly towards it."*
>
> *Grand Challenges are ambitious but achievable goals that harness science, technology, and innovation to solve important national or global problems and that have the potential to capture the public's imagination. These can have a major impact in domains such as health, energy, sustainability, education, economic opportunity, national security, and human exploration. Also, as various technologies such as biotechnology, information technology, and nanotechnology become more and more powerful—the question "what should we do" is arguably as or more important than "what can we do." This is not just a technical question, it is a question that relies on imagination, creativity, values, as well as individual and shared views on how we define progress.* (NEC & OSTP, 2015, p. 85)

Substantially the same wording can be found in Kalil's 2012 speech. The next section is about the path forward and describes the agency initiatives introduced above, as well as the commitment the Deans of Engineering have made, also introduced above. Finally, companies pursuing ambitious goals are mentioned: SpaceX, Google (self-driving cars), Qualcomm ("tricorder" like device), IBM (Watson). In this way the document makes the case that an all-hands-on-deck approach has been implemented because government agencies, universities and companies are engaged in the effort.[ix]

The White House approach to grand challenges clearly evolved between the first *Strategy for American Innovation*, published 9 months after President Obama was inaugurated, and the 2015 version. The first *Strategy* was similar to Engineering, Gates and Wilson in offering an 8 point to do list, though being in the noun form was somewhat of a throwback to earlier efforts. The list was also strangely un-grand (Goldston, 2009) and as if to remediate this, was followed by an RFI requesting suggestions for challenges from the public. The 2015 *Strategy* in contrast departs from previous models, reading less as a to do list and more as examples of a new policy tool at work. Indeed, the Administration seeks to improve government processes in part through pioneering new approaches to getting things done, itemized in the Innovation Toolkit (NEC & OSTP, 2015, pp. 109-110). One item in the toolkit is: "Identifying and pursuing the "Grand Challenges" of the 21st century."

Like Wilson, Gates and the Engineers, the White House is explicit about using grand challenges to energize a community and recruit new people into the effort. The White House is also explicit about working at scale. Ambition and potential for major impact are defining characteristics of the White House vision. The judgement that a solution is feasible, which was articulated by the Gates committee, was also articulated by Kalil. The White House made a public call for suggestions, like Gates and the Engineers. However, there is no eminent committee specifying a to-do list in the current White House vision, nor is explicit mention made of interdisciplinarity.

8. Similarities

The four most influential uses of grand challenges in US science policy have been introduced, as well as, briefly, a high profile competition[x]. Though they span 40 years, the efforts share a great deal. All are science policy in that they articulate an agenda in order to influence budget allocations. (This contrasts with the plethora of grand challenge academic papers and conference sessions proposing problem lists for a specialist research community.) They have in common elite sponsors – a Nobel prizewinner, the richest man in the world, the National Academy of Engineering, the White House.

At a fundamental level, the efforts share the dictionary definition. Grand means large or ambitious in scale or scope and also magnificent and imposing in appearance, size or style. In denoting the most important of its kind, it has connotations of nobility. A challenge is a call to take part in a contest or competition, originally a duel. The Grand Challenge usage is shifting this meaning. Rather than being offered by one man to another, the challenge is offered to society by a variety of forces beyond the control of any single person or institution. The intent is that we join together to overcome these predicaments. Grand Challenges have an air of saving humanity about them. Though this strand was not present in Wilson's formulation or the initial use by the computing community, it is notable in the Gates GCGH, Engineering and the White House efforts.[xi]

The efforts also hold in common a sense of what defines grand challenges in research policy. Grand challenges take the form of to do lists involving:

- Problems combining intellectual and practical obstacles (Wilson, Gates, Kalil)
- A desire to energize a community (Wilson, Gates, Engineers, Kalil/White House)
- At a large scale (Wilson, Gates, Kalil/White House)
- Requiring interdisciplinary research (Wilson, Gates)
- Specification by a committee (Gates, Engineers)
- A public call for suggestions (Gates, Engineers, White House)
- A request for resources (Wilson, Gates, Engineers)
- Judgment that solution is feasible (Gates, Kalil/White House)

This list represents the most elaborated definition in decreasing order of necessity. That is, all grand challenges are problem lists, fewer require feasibility. Gates Foundation Grand Challenges in Global Health articulates all these elements. The Engineers mention the fewest, not because they object to any of the defining elements but because their text is silent on so much, lacking even a definition of grand challenges. *Strategy* 2015 departs the most from this definition. Using grand challenges as an umbrella for innovative policy tools such as competitions and citizen science the Administration is moving the term into a new space tenuously connected to research.

Curiously, though the efforts should share a pedigree, they instead share the invocation of (various) aspirational pedigrees. Wilson doesn't mention the boat race or the Japanese Challenge, both of which likely influenced his phrasing. Rather he harkens back to the discovery of pulsars, an example anchoring his readers on an image of the excitement of big discovery. Gates doesn't mention Wilson or the HPCC, though he likely learned of grand challenges from Gordon Bell who was involved in the HPCC effort. Instead he anchors his readers' minds on an image of venerable abstract research with reference to the most influential mathematician of the 19th century. The engineers are silent on pedigree, as on much else. Kalil's speech does not mention Gates or Wilson or the boat race, pulsars or even Hilbert. He plants several anchors, harkening back to the moonshot, genome sequencing and Wikipedia (Kalil, 2012) offering glowing memories of a large, expensive and successful effort led by President Kennedy, a successful innovative big science effort, and a model of citizen engagement creating a broadly used knowledge resource. Each pedigree is offered with purpose, explaining grand challenges as something familiar in a particular way – exciting discovery, very, very scholarly science; or inspiring collaborative, citizen-involved efforts with presidential leadership. Each pedigree is aspirational and meant to suggest to readers that the author's plans will produce more success of the same type.

The four efforts share another characteristic - policy innovation. Wilson and the Gates Foundation pushed an outsider agenda and saw substantial success. Both initiatives can be interpreted as challenges to the post-war institutions governing US science. Both sought to place on the agenda of Federal agencies and scientists what they perceived as important problems that were being ignored: Wilson the development of high performance computing to advance science and Gates reducing the toll of infectious diseases in non-Western countries. Both succeeded in getting these items on the agenda. The US High Performance Computing act and subsequent programs, including one long running NSF grand challenge grant program, were helped into being by Wilson's advocacy. The Gates Foundation enlisted scientists to work on the problems of infectious disease in poor countries and saw NIH start to spend some money in this area. Several countries have partnered with the Gates Foundation to devote their resources to the effort. Others sought to expand the remit and rally resources behind efforts in non-communicable diseases and mental health in developing countries.

The other two initiatives came from institutional pillars of US science policy: the National Academy of Engineering and the White House Office of Science and Technology Policy. Far from being outsiders, these are consummate insiders and agenda setters. The engineering effort seemed to miss the mark, though two weakly linked efforts gained some traction, Singularity University and university programs to augment undergraduate engineering education. This is strange because one function of the report's genre, NSF funded National Academy studies, is to set priorities for research funding and the report's Grand Challenge list could be used for this purpose. The Administration's grand challenge efforts are associated with the President's initiatives to modernize the operations of the Federal government, in part by bringing in new policy tools such as prize competitions. The 2015 Strategy lists grand challenges as one item in an "Innovation Toolkit for Public-Sector Problem Solving" (NEC & OSTP, 2015, p. 109). The agencies' grand challenges use competitions and seek participation beyond university scientists, both new elements in US science policy.

The four science policy grand challenge initiatives examined here share origins among the elite, a definition of grand challenges, persuasive use of aspirational pedigrees and innovative intent. The next section takes a closer look at the innovative aspect by considering the relationship between grand challenges and the older, dominant framing of research efforts as basic or applied.

9. Grand Challenges versus applied research

These four initiatives were motivated by different dissatisfactions with current policy: lack of funding for supercomputers in physics, lack of scientific attention to infectious diseases in developing countries, lack of public enthusiasm for engineering, little public engagement with Federal government and a feeling that more advantage could be taken of innovative processes used in the private sector. Yet as different as these motivations were, elites pursued their programs under the rubric of grand challenges, as if beyond the dictionary definition of the individual words, the phrase somehow signals innovation in research policy.

In US research policy, basic and applied research, the linear model, and the scientific frontier have been invoked almost *ad nauseam* by those garnering broad political support for large scale funding commitments to research in the decades since World War II. After 60 years, this discourse seems to have lost some of its force. For example arguments have been made that society can no longer condone basic research that causes suffering to animals (Bateson et al. 2011; Greek and Greek, 2010), suggesting the domain of basic research could contract. Pielke charts the declining usage of "basic research" in *Science*, *Nature,* the *New York Times* and Congressional Hearings during the 2000s (Pielke, 2012). In books scanned by Google, use of "basic research", originating about 1940, peaked about 1986 and declined thereafter. If one discourse loses some of its persuasive power, does research therefore command less attention and lower political priority? Or might new schema emerge to fill a developing void?

The grand challenge concept does not overturn the modernist institutions of science policy established after World War II. Rather it represents a new discourse, a new way of seeing things that persuasively framed initiatives outside the normal schemas. I use schemas in Sewell's sense as cultural resources, less the hard and fast rules such as those that govern the NSF and NIH and their grant programs, but instead the binary oppositions providing fundamental tools of thought, informal metaphors, assumptions, conventions, scenarios and habits of speech (Sewell, 2005, p. 131). Sewell argued that the unavoidable metaphor of structure in the social sciences, is constituted by mutually sustaining cultural schemas and resources that empower and constrain social action and tend to be reproduced by that action. To Sewell structure is dynamic, evolving through actors' resourceful agency and interaction (Sewell, 2005, p. 151).

Maarten Hajer has traced the evolution of schemas in the domain of environmental policy, pointing to widespread to dissatisfaction with modernist policy institutions (Hajer, 2003). His work demonstrates how a new environmental discourse:

> *. . . brings to life a new way of seeing, with new constraints and new opportunities, that is then recognized and interpreted by various actors within the environmental domain, which subsequently leads to all sorts of adjustments in institutional practice. (Hajer, 1995, p. 262)*

Grand challenges may have the same potential to be a new way of seeing research. It has been used by those seeking innovation in research policy perhaps for that reason. In research policy the dominant modernist schema, the one the audience for grand challenges uses to interpret what is being said, would be basic and applied research, the linear model and the frontier of science. The category of basic research emerged after WWII and is associated with Vannevar Bush's report: *Science the Endless Frontier* which changed forever the language of science policy with an explanation of how basic research enabled societal progress, associating it with the excitement of the American exploration of the frontier (Bush, 1945). Basic research connotes not only research done with no consideration of application, but also autonomy of the individual exploring the frontier, superiority over applied research (Stokes, 1997) and the linear model encapsulating the relationship to societal need. The inadequacy of this framework has been noted before (for example, Ceccarelli , 2013; Pielke 2012) and attempts have been made to develop a new language with which to describe research (Stokes, 1997; Nowotny et al., 2003). I have suggested above that grand challenge initiatives agree on proposing lists of problems that combine intellectual and practical aspects. This combination defined Pasteur's Quadrant (1997), Stokes' proposed new language, and it echoes Mode 2's context of application (Nowotny et al., 2001).

Speaking in terms of grand challenges, one can avoid the basic/applied categories. Even better, grand's connotations of nobility perhaps evades any hints of inferiority that might be expected to accompany mention of solving practical problems (Stokes, 1997). Engineers have always had a status problem in the basic/applied world. Connotations of nobility and grandeur in problem solving would have obvious attractions to those tasked with making engineering seem desirable. Transcending basic/applied would have been useful to Wilson whose project risked being seen as applied and therefore of lower status. The type of advocacy he rejected, pointing to problems solved, is used when arguing for money for applied research. His use of grand challenges conveys excitement associated with big discovery (pulsars) and working with purpose while avoiding the low status associated with applied. Wilson's definition of grand challenges does not use the word "applied", preferring instead: benefits, basic, extreme difficulties, extraordinary rewards.

That the modernist schema always lurks in the background is suggested by Gates' invocation of abstract mathematics to introduce his problem solving grant program. The otherwise anomalous introduction of Hilbert into Gates' *Wall Street Journal* piece makes sense if viewed as an attempt to signal appreciation of scientists' valued basic research and, despite the large amount of money on offer, a concern to be seen as credible in the world of science by a new entrant whose reputation was built in technology and whose Foundation at that point delivered healthcare services.

The modernist schema is never very far away in people's minds and so frames their reception of the grand challenges concept. The most common framing is to see the new language as another way of talking about applied research. Mode 2 suffered this fate (Nowotny et al., 2003). The wording in the US Code associated with the HPCC defines grand challenges as application of computing to science. The same approach was taken in a special issue of *Research Policy* on Grand Challenges devoted to gleaning lessons learned from the history of mission oriented research, the idea being that grand challenges are another name for mission oriented research. However, within that issue, the differences between Grand Challenges and mission oriented research were noted: greater breadth, longer time scale, no single agency being the intended "user", intersectoral research collaboration required, competitive environment of application, and many sources of R&D funding (Foray et al., 2012, p. 1698).[xii] Thus the article itself admits that equating grand challenges with classical-modernist mission oriented research doesn't work, if grand challenges are framed according to the definition given above.

The White House, being the center of the establishment, can be expected to have particular problems transcending the categories that govern establishment thinking. In the manifesto, Kalil proposed a definition encompassing both breakthroughs in science and technology and goals, thus framing a concept melding both intellectual and practical problems. *Strategy* 2015 dutifully begins with a short section on fundamental research reviewing the President's commitment to funding for NSF and NIH. In this context, where use of the basic category is mandatory, grand challenges did not maintain the character of research combining intellectual with practical challenges. "Harnessing science, technology and innovation" to address goals seems much more like a call to do applied research, and grand challenges has been implemented in agency mission specific programs. Though as noted above, these programs still do not look like mission oriented research because although they are agency mission oriented, they are not exactly research programs. The reduction to applied research also appears in the common rewording of grand challenges to societal challenges. Societal challenges can be juxtaposed with scientific challenges (Neal et al. 2008), and very little need change.

The history of grand challenges in US science policy demonstrates that changing schema is extremely difficult. The grip of the existing ways of thinking remains very strong. Only powerful elites are able to have a lasting impact with new discourse, and even then, the pull of the old categories cannot always be overcome.

10. Conclusion

In contrast to the tired categories of basic and applied, grand challenges offers a research agenda more appropriate to our times, one that combines intellectual and practical motives, generating excitement to address problems so big that they exceed the capacity of specialist communities. All the more so when articulated as a list, lists being "the signature form of our time" (O'Connell, 2013). The grand challenge concept appeals today as an invitation to join a larger effort and connect with public concerns and thus stands opposed to the bygone era of lone scientists in ivory towers. Grand Challenges evoke excitement; in the context of research that would be intellectual excitement. In every example examined here, although the grip of the older categories remained strong, grand challenges demonstrated potential as a new language.

If the potential of grand challenges were to be deployed consistently, basic research could come to seem anachronistic. “Investigator initiated” sounds individual which could become a liability in an age of team science, networks and collaboration. Working well together might be the new ideal in scientific life, insistence on individual pursuits might soon sound somewhat selfish. Basic research would also be tainted when described as research “without a goal.” Formerly, research was tainted when performed with a goal in mind, but in an era guided by conceptions of grand challenges as the right and proper framing for science policy, the taint could well transfer to research that cannot show a connection to a grand challenge. Grand challenges encapsulate the promise of intellectual excitement and align with the group effort that characterizes research today, transcending limits imposed by an aging vocabulary of basic, applied and mission.

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[i] http://www.cac.cornell.edu/about/history.aspx accessed June 5, 2013

[ii] One of which was basic research.

[iii] Grand Challenge lists mentioned in this paper can be found at www.dhgc.weebly.com

[iv] Cited 1.6 times as often as the GCGH launch paper: Varmus et al., 2003, *Science*.

[v] Though Gates' readers are reassured that research into these problems "led to significant breakthroughs in technology and medicine."

[vi] In June 2016 Google returned over 600 hits on a search of singularityu.org for "grand challenges".

[vii] Hilbert, the Gates GCGH and the Academy of Engineering list were mentioned in an earlier document, a 2009 RFI calling for public input on grand challenges.

[viii] https://youtu.be/i6v5EFYnPjE

[ix] The all-hands-on-deck wording is used elsewhere in the document to refer to initiatives in K-12 STEM education and entrepreneurship efforts that also involve working collaboratively with institutions outside the government to accomplish policy goals.

[x] The next most influential use would be the National Academies report on Grand Challenges in Environmental Science, and following that, other National Academies reports. The environmental report was influential within the environmental science community. It's characteristics mirror those described here.

[xi] If one isn't ultimately working to save humanity, can the challenge truly be grand?

[xii] The reduced control of a single agency over the activity in question goes to the heart of the difference between the modernist and deliberative policy environment described by Hajer (Hajer, 2003).