Governance mechanisms enabling inter-organizational adaptation: Lessons from grand challenge R&D programs

By: Christopher S. Hayter and Albert N. Link

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Abstract:

From climate change to terrorism, the world is confronting complex, trans-national problems. As a contemporary response, governments and non-profit organizations have established grand challenge programs, consisting of multi-sector research and development partnerships, to access innovative new ideas and rapidly scale solutions. Following recent scholarly contributions, this article investigates how problems motivating program establishment were identified, how these problems and related contextual factors evolve over time, and how grand challenge programs evolve in response. It does so through a multi-year study of ten grand challenge programs that differ substantially in purpose and organization. This article finds that adaptive capabilities—inter-organizational governance mechanisms—and operational aspects such as purpose, scope, temporal factors, and partner capabilities are critical to program evolution and impact.

Keywords: grand challenges | R&D partnerships | governance | innovation policy

Article:

1. Introduction

In 2003, Microsoft founder Bill Gates announced a $200 million grant from the Bill and Melinda Gates Foundation (BMGF) to establish Grand Challenges in Global Health (Gates 2003). The articulated objectives of this program were to identify and support novel, interdisciplinary approaches for improving global health in the developing world. Gates established the program as an opportunity to contribute to the betterment of society in ways that market forces had not (Gates 2003: A61):

> Market-based capitalism works well in driving scientific research. But to accelerate research into diseases in the developing world, market forces alone are often not enough

> … the role of philanthropy, in the best sense, is its ability to place a value on things that the market does not.

Grand challenge initiatives or programs are not new, as discussed by Kalil (2006, 2012).[1] More recently, Hayter (2015) defines grand challenge programs as multi-organization, solution-oriented research and development (R&D) initiatives. The author finds that the establishment of grand challenge R&D programs was driven by the trans-regional and trans-national nature of humanitarian problems, such as climate change, food security, and neglected diseases. Echoing Gates' comments above, grand challenge programs have been established in response to a single organization, sector, or country not having the financial or scientific resources, or capabilities to address such problems (Kettl 2015; Nowotny et al. 2001; Shrum et al. 2007). In other words, the partnership orientation of grand challenge programs can provide access to innovative new solutions to complex problems and enable the implementation of these solutions at scale.

Recent empirical studies examine the design and function of grand challenge programs. Modic and Feldman (2017), for example, examine initiatives in the European Union (EU) and USA that seek to understand and treat diseases, such as autism and schizophrenia, related to the human brain. Kuhlman and Rip (2018) focus on grand challenges within the broader context of innovation policy evolution describing them as '[N]ew constellations of innovation actors' that have emerged to address specific societal problems (448). Both papers find that governance—what Modic and Feldman (2017) term *institutional frameworks*—is critical to the function and impact of grand challenge programs, especially regarding how problems are identified as well as how programmatic responses are implemented.

Although prior to these recent scholarly contributions Eisenhardt et al. (2016) suggest that significant opportunities exist to explore the emergence, governance, and especially the evolution of grand challenge programs, these opportunities are further highlighted in the public management literature; that literature ties the impact of multi-sector partnerships to the structure and evolution of their governance mechanisms (Bryson et al. 2015; Emerson et al. 2012). This article helps address the gap in the literature identified by Eisenhardt and Bryson, and their colleagues, by focusing on what Kuhlman and Rip (2018) call the 'meta-governance' and 'concertation and assemblage' of grand challenge programs. Specifically, this article focuses on how grand challenge programs are established and how they evolve in response to rapidly-changing problems and contexts. Through a multi-year study of ten grand challenge programs, we offer insight into how governance mechanisms for defining and selecting grand challenge problems and organizing solution responses evolve.

Our study finds that adaptive capabilities—the capacity of grand challenge programs to adapt their governance structures to ever-changing problems and contexts—are critical for these initiatives to have their desired impact. Further, grand challenge programs have established

[1] For example, German mathematician Hilbert articulated the twenty-three most important unsolved grand challenges in mathematics during the International Congress of Mathematicians held in Paris in 1900. Also known as 'Hilbert's problems', these challenges were intended to spur *collaboration* (emphasis added) within the entire international community of mathematicians while inspiring the next generation of scholars (Reid 1996). See also Hicks (2016) for a discussion of early involvement of the US federal government in, for example, high-speed supercomputing.

decentralized and centralized mechanisms for problem identification and selection as well as solution implementation. The effectiveness of these varying approaches depends on the goals and inter-organizational context of the program.

The remainder of the article is organized as follows. Section 2 briefly reviews the partnership governance literature as well as recent studies on grand challenge programs. Section 3 introduces the study methodology while Secion 4 presents our research findings. Finally, Section 5 discusses the implications of our findings, including considerations and suggestions for policymakers and practitioners interested in establishing grand challenge programs that relate to operational goals, problem scope, temporal aspects, and partner capabilities.

2. Conceptual background

Scholars have recently highlighted the emergence of complex, systemic problems in society such as climate change, large-scale population migration, and vaccine development for the developing world (Kettl 2015; Koppel 2010). These problems are viewed as public value failures, which means that they are characterized by scarcity of service providers, lack of market-driven value articulation and aggregation mechanisms, imperfect monopolies, and short-term horizons and benefit hoarding (Bozeman 2002). What makes such problems grand challenges is their scale and scope, as well as society's required collaborative response to them (Hayter 2015).[2]

There is increasing recognition that local as well as national governments cannot alone address complex trans-national problems; and if they try, the resources used for their responses should not be limited to the public sector (Kettl 2015; Kuhlman and Rip 2018). A number of researchers (e.g. Koppell 2010) have argued that scholars and policymakers should conceptualize problems in terms of global governance whereby governance is defined as 'lateral and inter-institutional relations in administration in the context of the decline of sovereignty, the decreasing importance of jurisdictional borders, and a general institutional fragmentation' (Fredrickson 2012: 235). A governance-oriented approach to problems assumes that responses will include organizations 'across sectors and civil society in order to address public problems that they cannot successfully address alone' (Bryson et al. 2015: 647).

While governance-related approaches have been employed to address a number of problems in society, such as disaster response (Tierney 2012), watershed management (Koontz and Newig 2014), and vaccine development for poor countries (Hayter and Nisar 2017), scholars have only recently employed governance frameworks to describe fundamental transformations in innovation policy (e.g. Kuhlman et al. 2019). Specifically, researchers describe the emergence of grand challenge programs, multi-sector R&D partnerships designed to address complex, trans-national problems (Hayter 2015) that cannot be effectively addressed by technology supply push or demand policy instruments (Kuhlman and Rip 2018). Grand challenges thus represent new constellations of actors that employ 'tentative governance' comprised of 'provisional, flexible,

[2] Emerson and Nabatchi (2015: 6) posit that the demand for governance-related approaches is based on, among other factors, the emergence of so-called wicked problems; and they cite Rittel and Webber, who refer to these problems as being 'difficult or impossible to solve because of incomplete or contradictory information, rapidly shifting environments, and complex interdependencies' (Emerson and Nabatchi 2015: 6).

revisable, dynamic and open approaches that include experimentation, learning, reflexivity, and reversibility' (Kuhlman et al. 2019: 1091).

In one of the few empirical investigations of grand challenge programs, Modic and Feldman (2017) examine efforts in the EU and USA to map the human brain in order to understand and treat related diseases, such as schizophrenia and autism. To understand the effectiveness of the two brain-focused grand challenge initiatives, the authors posit that it is critical to understand the institutional origins of these programs as well as their implementation (i.e. context). First, the authors chronicle aspects of public agenda-setting efforts that led to the identification and selection of brain diseases as a grand challenge problem within the EU and USA. Second, the authors focus on institutional frameworks that '[E]nable them to determine: who participates, how resources are allocated, and how inevitable disputes should be addressed and resolved' (443). Similar to Kuhlman and Rip (2018), Modic and Feldman (2017) further emphasize the importance of grand challenge problem uncertainty and the related importance of program evolution.

In sum, grand challenge programs are a type of multi-sector partnership that promotes collaboration and resource pooling among partners from multiple sectors. Further, these collaborative governance arrangements likely enable participants to pool risk, which is critical given the inherent uncertainty associated with the complex research endeavors (Goel, 2007; Kamien and Schwartz 1982). The next section describes the methodology used in the study.

3. Methodology

Eisenhardt et al. (2016) recommend that grand challenge-related research focus on '[Q]uestions that address "how" and "why" in unexplored research areas' (Eisenhardt and Graebner 2007: 26–7).[3] Of particular interest are investigations of grand challenge program 'configurations, emergence, and equifinality' (Eisenhardt et al. 2016: 1116). Following the recent contributions and opportunities in the literature (e.g. Kuhlman and Rip 2018; Modic and Feldman 2017), this project thus investigates the following research questions: (1) How were grand challenge problems that motivated program establishment identified? (2) How did grand challenge problems and related contextual factors evolve over time? (3) How did grand challenge programs evolve—if at all—in response to these changes?

Our study addressed these questions through multiple case studies which, according to Eisenhardt et al. (2016), help to explain variances in grand challenge-related processes or outcomes of interest (Eisenhardt 1989; Eisenhardt and Graebner 2007). Cases were selected following Hayter's (2015) definition of organizations that: (1) are so-termed 'grand challenge programs', (2) focus primarily on addressing complex social problems, and (3) consider R&D a critical component of their operations. Based on these criteria, ten programs (Table 1) were selected to provide in-depth understanding of specific grand challenge programs and maximize theoretical heterogeneity (Eisenhardt and Graebner 2007); diverse cases provided the research

[3] Maxwell (2008) similarly posits that qualitative methods are especially effective for explaining how and why a phenomena occurs, especially from a process perspective, utilizing questions about (1) the meaning of events and activities and (2) the related influence of the physical and social context.

team with multiple opportunities to examine both commonalities and unique facets of each grand challenge program.

The ten programs were established at different times by disparate government and non-profit organizations including universities (e.g. Arizona State University, ASU), foundations (e.g. the BMGF), government agencies (e.g. Defense Advanced Research Projects Agency [DARPA]), and social research institutions (e.g. Smithsonian Institution). Further, the selected grand challenge programs vary in focus and scale. The purpose of programs in our sample range from creating multi-disciplinary research projects among faculty and graduate students at New York University (NYU) to Grand Challenges Canada which establishes multiple multi-million dollar initiatives among governments, foundations, and industry to improve health outcomes in the developing world.[4]

3.1 Data collection

This study relies on both retrospective and contemporaneous data collected through program documents, archival records, and in-person and telephone interviews. Data were collected during two research phases between 2010 and 2014 (Table 2). During the first phase, the research team established points of contact at each of the ten grand challenge programs. These individuals provided the research team with program documentation, and they committed to introducing the research team to relevant individuals over the course of the four-year study.[5]

Following Gioia et al. (2012: 17), criteria were used to guide the selection of 'knowledgeable agents' with whom the study team would speak. First, these groups of individuals had to have participated directly in the establishment and operation of their respective grand challenge program, and they had to have been present as the program evolved over time. Second, these groups needed to include individuals with diverse perspectives, meaning representatives from one of several participating organizations, including the organizing institution, partner governance organization(s), financial resource organizations, or organization(s) with hands-on involvement in implementing solutions. Finally, individuals in the groups had to have an objective view (i.e. this worked, this did not work) of the implementation strategy of the program.

[4] We are not arguing that our sample of 10 programs is representative of the universe of grand challenge programs; rather, following Eisenhardt et al. (2016), we are emphasizing our effort to capture the heterogeneity of the various forms and areas of emphasis within the universe of grand challenge programs.

[5] The research team included the authors of this article and two research assistants who are expert in qualitative methods and the design and evaluation of science and technology policy.

Table 1. Grand Challenge Programs examined in the study

Name	Established	Organization type	Program purpose (or definition)	Technical focus areas	Partners
ASU	2011	University	The program's goal is to prepare tomorrow's engineering leaders to solve the grand challenges facing society during the next century. Through completion of the five components of the program, students will have the opportunity to engage in research relating to their selected grand challenge, explore interdisciplinary coursework, gain an international perspective, engage in entrepreneurship, and give back to the community through service learning.	Student driven based on NAE 14 priorities; common themes include food, water, health, and energy	Various departments within the engineering school; individuals from other departments, schools, and organizations
The Belmont Forum Challenge	2011	Consortium of national research funding agencies	To deliver knowledge needed for action to avoid and adapt to detrimental environmental change including extreme hazardous events.	Climate change and the environment	Multiple; partners from all sectors
DARPA Grand Challenge Program (2005 definition)	2004	Government	[The] DARPA Grand Challenge is a field test intended to accelerate R&D in autonomous ground vehicles that will help save American lives on the battlefield. The Grand Challenge brings together individuals and organizations from industry, the R&D community, government, the armed services, academia, students, backyard inventors, and automotive enthusiasts in the pursuit of a technological challenge.	'Driverless' robotics-based vehicle technology	Teams (competitors) from universities and companies; personnel from Department of Defense and other agencies
Grand Challenges in Global Health: BMGF	2003	Foundation	A call for a specific scientific or technological innovation that would remove a critical barrier to solving an important health problem in the developing world with a high likelihood of global impact and feasibility. Grand Challenges (program) is a family of initiatives fostering innovation to solve key global health and development problems	Evolving; since establishment, problems of human health.	Multiple; partners from all sectors
Grand Challenge Canada	2011	Government	A grand challenge is a specific critical barrier that, if removed, would help solve an important health problem in the developing world, with a high likelihood of global impact through widespread implementation.	Human health	Multiple; partners from all sectors
NAE	2011	Non-profit honorific organization	In each of these broad realms of human concern—sustainability, health, vulnerability, and joy of living—specific grand challenges await engineering solutions. The world's cadre of engineers will seek ways to put knowledge into practice to meet these grand challenges. Applying the rules of reason, the findings of science, the aesthetics of art, and the spark of creative imagination, engineers will continue the tradition of forging a better future.	Fourteen various engineering challenges	Multiple engineering universities

Name	Established	Organization type	Program purpose (or definition)	Technical focus areas	Partners
NYU	2013	University	Grand Challenges promote significant scientific research that has the potential to solve major national or global problems. The aim of the Grand Challenge (program) is to support ambitious but achievable goals that harness technology to solve important societal and health problems.	Open; faculty driven	Individual faculty from various colleges and departments within the university
Princeton University	2007	University	The Grand Challenges Program is an ambitious and broadly inclusive initiative at Princeton designed to tackle these complex and vexing global environmental problems by fully integrating the research and teaching missions of the University. The Program engages faculty from disparate disciplines with postdoctoral fellows and students at all levels of the Princeton University community to examine the scientific, technical, public policy, and human dimensions in the areas of climate and energy, water and the environment, sustainable development, and global health.	Climate and Energy; Water; Health; Development	Individual faculty, postdocs, and students from various colleges and departments within the university
Smithsonian Grand Challenge Consortia	2010	Non-profit museum and research organization	Smithsonian Grand Challenges Awards—a competitive, internal granting program—advance cross-disciplinary, integrated scholarly efforts across the Institution which relate to the Smithsonian Grand Challenges: unlocking the mysteries of the universe, understanding and sustaining a biodiverse planet, valuing world cultures, and understanding the american experience. These awards encourage Smithsonian staff to advance research, as well as broaden access, revitalize education, strengthen collections, and encourage new ways of thinking that involve emerging technology.	Learning and research related to the Smithsonian's education and research mission	Various departments within the organization
US Agency for International Development	2011	Government agency	The Grand Challenges for Development initiative is rooted in two fundamental beliefs about international development: (1) Science and technology, when applied appropriately, can have transformational effects; and (2) Engaging the world in the quest for solutions is critical to instigating breakthrough progress.	Health; food security; agriculture; government accountability	Multiple; partners from all sectors

Table 2. Interviews conducted during research phases (sixty-two total)

	Phase I (2010)	Phase II (into 2014)
Initial respondents	27	20
New for Second phase	–	15
Total	27	35

Forty-two individuals were interviewed during sixty-two separate interview sessions over the course of the four-year study. As shown in Table 2, the first phase included twenty-seven individuals, twenty of whom were included in the second phase interviews, along with fifteen additional individuals, at least one new person from each program was interviewed in the second phase. Following Seidman (2013), the study team conducted most of its interviews by telephone, guided by a semi-structured interview protocol designed to focus on the establishment and structure of the particular program, the social and economic context in which they and the program operated, and how the program evolved over time. Interviews for collecting data ranged in length from 30 min to 2 h, with most lasting approximately 45 min. All interviews were recorded and transcribed; a memo was created after each interview summarizing the study member's observations.

The research team took purposeful steps to increase internal validity. In contrast to quantitative techniques, the validity of qualitative research is defined as 'how accurately the account represents participants' realities of the social phenomenon and is credible to them' (Creswell and Miller, 2000: 124–5). Following procedures outlined in Creswell and Miller (2000), the study team sent an interview summary to each participant within two weeks for validation, along with a request for an additional telephone conversation if any clarification was needed.[6] The study team also sent interview summaries to the other program points of contact for their review and comments. Finally, the derivative manuscript was sent to external scholars with experience working with governance concepts and three other scholars with experience studying grand challenge programs for their comments and interpretative suggestions.[7]

3.2 Data analysis

Once each round of data collection was completed, interview transcripts and memos were coded by the study team,[8] according to procedures recommended by Kuckartz (2014) and Saldana (2012). Further, the study team drew from Gioia et al. (2012: 20), who describe a process for analyzing and aggregating data to demonstrate rigor in the conduct of qualitative research. Specifically, an initial round of open coding (Corbin and Strauss 2008) was conducted by hand, supplemented with an analysis utilizing NVivo software, that generated the related first-order concepts. The research team then moved to the construction of axial coding second-order (axial)

[6] Creswell and Miller (2000) term this approach 'member checking' whereby researchers are 'taking their data and interpretations back to the participants in the study so they can confirm the credibility of the information and narrative account' (127).

[7] Creswell and Miller (2000) term this stage the 'validity audit'.

[8] The research team comprised four individuals, including the two authors, both tenure-track professors, and two research assistants. One author and one research assistant coded the data, asking the other research assistant to resolve ties related to divergent data interpretations. Inter-coder reliability, the extent to which independent coders evaluate reported data and reach the same conclusion (Neuendorf, 2002) improves data quality. Using (1) per cent agreement and (2) Krippendorff's (2004) alpha, coded variables exceed accepted thresholds of inter-coder reliability, 90 per cent and 0.800, respectively.

themes to understand the relationship among open codes within and across different types of interviews, generating second-order themes. Throughout, the research team moved between the data and the emerging data categories for refinement. Finally, the study team composed aggregate dimensions, discussed in detail in the following section.

4. Findings

The findings from our study are discussed in this section. Following the study's research questions, they are segmented into three sections: (1) the identification and selection of grand challenge problems that motivate program establishment, (2) how grand challenge problems and related contexts evolved over time, and (3) how programs evolved, if at all, in response.

4.1 Problem identification motivating program establishment

We found that the establishment of grand challenge programs was motivated by the identification of complex problems in society and the desire to address these problems in collaboration with like-minded partners. Grand challenge problems were identified in three distinct ways, including: (1) top-down specification of focus, (2) top-down specification of direction, and (3) participant-driven focus.

First, programs are established based on problems defined by founders, often refined by *ad hoc* or standing advisory groups. For example, the BMGF established the Grand Challenges in Global Health program as a result of several visits by the Gates family and the Foundation staff to the poorest regions of Africa and Asia. While the BMGF focused early philanthropic efforts on the Pacific Northwest region of the USA, these visits were deemed by the BMGF officials as:

> The spark for our grand challenges program … they really highlighted the health-related disparities, especially the incidence of chronic disease. We realized that what we took for granted here [in the US] … that we spend a few dollars per person each year on vaccines … is out of reach for people in the poorest nations. Bill and Melinda Gates basically said 'we are going to do something about this.'

The BMGF and Grand Challenge Canada defined further their initial (broad) emphasis on improving global health through advisory groups that identified and prioritized specific health problems, guided by specific criteria. Health challenges prioritized by Grand Challenges Canada must: (1) have the greatest opportunity to improve global health, (2) not be the focus of other grand challenge efforts but have the potential to attract partners, and (3) can feasibly be incorporated into their operating strategy. Through these processes, Grand Challenges Canada has prioritized mental health and early childhood brain development, among several other focus areas, as critical to their mission.

Another group of programs defined their direction broadly, allowing participants a degree of autonomy in how they address a grand challenge problem. For example, The National Academy of Engineering (NAE 2006) convened a 'blue-ribbon' panel of leading thinkers from technology, science, business, politics, and engineering to articulate fourteen grand challenges as the basis for an NAE-sanctioned engineering curriculum. These fourteen grand challenges provide problems

to guide the development of engineering curricula and programs at universities across the USA. At ASU, for example, the fourteen grand challenges serve to guide student teams who, in cooperation with faculty and outside partners, seek to address them. However, student teams have enormous latitude with regard to their challenge focus as well as to how they address these challenges.

Similarly, the then DARPA Director, Dr. Tony Tether, and his staff chose to focus the 2004 Grand Challenge competition on the development of autonomous vehicles (AVs) because the enabling technologies had been previously identified as an area of strategic interest to the US Department of Defense (DoD). Further, the Director and his team were motivated by the expiration of legislation passed in 2000 that provided DoD with the authority to use the so-called inducement prizes for innovation.[9] While the program was structured as a 150-mile competition in the Mojave Desert among teams and their autonomous vehicles, it did not specify specific technological priorities but instead left it to participants as to how they would complete the race.

In contrast to programs that define grand challenges at varying levels of specificity, programs at Princeton University, NYU, and the Smithsonian Institution enable participants to define the grand challenges they intend to address to take advantage of their knowledge and creativity. For example, according to a program coordinator at Princeton, intra-organizational programs are critical because:

> Top-down organizational strategies don't really work in academic environments … scientists are incentivized to develop their reputations as individual scholars … so you have to provide incentives for them to work together to identify and work toward a common problem. The wonderful part of the program is that what can result are projects that no one would have anticipated.

The Smithsonian Institution Grand Challenge Consortia similarly focuses on finding 'areas of common interest and potential innovation among our experts … within one of the most unique cultural institutions in the U.S.' However, program directors at universities spoke about the difficulty of including partners from outside their organizations to identity and collaboratively address grand challenges: 'it is difficult to find and work with individuals in government labs or companies who we could provide a very different perspective … we need their views when thinking about how to solve a problem but they rarely have the opportunity to get away from their day-to-day roles to think about big, grand challenge issues.'

While the Smithsonian and university programs do not define specific challenges, program participants are guided by criteria. At NYU, for example, proposed solutions must have the potential to create a substantial impact in society, especially on the lives of the people of New York; be team-based, including individuals from different disciplines; and, have potential to attract funding and partners from government and industry. According to a university program director, 'this approach works well for scientists. They are the experts … and this program encourages them to work with others to do something big and exciting … we think that's the key to impact.'

[9] See, for example, Kalil (2006) and Williams (2012) for a more in-depth discussion of innovation prize models.

4.2 Problem and context evolution

According to study respondents, grand challenge program success over time depends on the capability to recognize how problems themselves evolve. Within the context of engineering curriculum guidelines articulated by the NAE Grand Challenge program, respondents spoke of the need to:

> …[O]ccasionally update the [original] problem definitions and provide additional detail to the program … frequent changes are unnecessary because these [grand challenge] problems will be around for a long time. The accreditation process doesn't allow for drastic changes which generally allows us to keep track of what's going on among the challenges.

The NAE panel of high-level experts has thus been periodically reconvened, most recently in 2017, to update the curriculum to enable undergraduate engineering students to learn and work within the context of evolving grand challenges.

Other programs possess standing advisory committees with rotating members who provide an understanding of how grand challenge problems evolve. For example, Grand Challenge Canada's advisory committee provided insights into ongoing advancement on how pre-natal health and nutrition affects brain development. This knowledge allowed the program's Saving Brains Initiative to avoid duplication among other brain-related efforts and focus on developing games and educational tools to stimulate and accelerate brain development among poor children in Africa.

The BMGF not only convenes advisory committees, but they have also hired program staff to monitor relevant academic and clinical research on diseases related to their vaccine development efforts. For example, detailed analyses of ongoing research led BMGF staff to understand the relationship between AIDS and tuberculosis (TB): a disproportionate number of AIDS victims die from TB. This knowledge informed the foundation to direct vaccine development efforts toward the interaction of the two diseases, rather than only develop separate vaccines for each disease. Further, BMGF collects systematic data from international organizations (e.g. Doctors Without Borders) that work in the communities the BMGF is attempting to help to understand the impact of these diseases and cultural receptivity to how vaccines are administered.

While the DARPA grand challenge competitions do not have a standing advisory body, they draw upon DARPA personnel and consultants to work with qualifying participants. These individuals ensure that participants understand competitions requirements and shepherd them through the competition process while gaining important insights into their technological capabilities. According to a DARPA official involved in the grand challenge competitions:

> DARPA likes to stay agile … we make sure we are talking to the teams before, during, and after the [grand challenge] competitions. Through these conversations, we get a window into the latest AV [autonomous vehicle] technology … and that allows us to focus on planning the competitions … and how we can help the teams.

In other words, DARPA's relationship with the participating teams provides an understanding of the technical challenges of developing and deploying AVs, and thus shapes current and subsequent AV development efforts either through the grand challenge program or among other DoD technology development mechanisms.

While all grand challenge programs in the study were established with the help of advisors or an advisory committee, some programs did not maintain the capability to understand how changes in context affect how the problems should be addressed. One United States Agency for International Development (USAID) program was established to address complex public health challenges among countries in the former Soviet Union. However, during the course of the study (in 2012), the Russian government expelled USAID staff because they had provided support for non-governmental organizations that were opposed to the policies of President Vladimir Putin. A USAID representative involved in Eastern European and Russian programs described the challenge.

> Several years back, we drew from a lot of smart people who know Russia to set up our [grand challenge] program … but that's where it [their involvement] ended. It gets going and then we get kicked out. We knew that the Russian government wasn't happy with our democracy-building efforts. But we didn't have a pulse on the entire political situation and were taken by surprise … we didn't really think they'd touch public health. We should have stayed in front of this.

Similarly, staff representing a program designed to preserve the habitat of endangered species described why they did not possess the capability to understand how their target challenge was changing: 'we lack people on the ground who understand how [these species] interact with their environments … how this changes. This means that our current understanding of the problem is based on views from about six or seven years ago … and we know that is just too long.'

Interestingly, all grand challenge programs in the study had conducted *ad hoc* studies or possessed internal capabilities to evaluate program impacts. However, many programs viewed the ability to understand how problems and context were changing separately. One notable exception is Grand Challenges Canada, which views ongoing understanding of the problem and context as a key component of how they measure program success. According to a program official:

> I am not sure how you can evaluate the effectiveness of an initiative like Saving Brains without understanding how this moving target of brain health in very dynamic … often unstable environments. We work in places that might enjoy peace and stability one month … and then the next they are beset by famine or war or disease. We can't make much of an impact if we don't take these things into account as we think about program success … and impact.

For the Belmont Forum, an understanding of evolving contexts is also important to program support and sustainability. For example, program initiatives related to climate change have benefited from understanding better shifting public awareness and opinions about the impacts of climate change around the world. According to a representative of the program, 'we have

benefited from analyzing who is increasingly concerned about climate change … this let's be focused on who we work with, how to focus on their specific concerns, and turn that into financial support for our programming … it's a virtuous cycle … and that translates into impact.' In short, the capability to understand context is just as valuable as understanding how the grand challenge problem evolves.

4.3 Grand challenge program responses

The previous section focused on how grand challenge problems evolved along with programmatic mechanisms designed to understand these changes. This section focuses on how grand challenge programs responded to these evolving conditions once they understood how the problem changed—and how, according to respondents, it related to program success. Two types of governance responses emerged from the data: decentralized and centralized responses.

A decentralized governance response means that grand challenge programs delegate responsibility for addressing grand challenge problems to program participants. For example, the Belmont Forum defines specific grand challenge problems that relate to climate change but responsibility for implementing the program's research agenda lies with program participants, usually national R&D agencies, among other partners. Similarly, teams of faculty, postdocs, and students selected for the Princeton Grand Challenge program are expected to use program funds and resources to submit funding proposals to large-scale, federal grant programs. According to study participants, a decentralized response that prioritizes multi-disciplinary collaboration works well when success is defined in terms of obtaining academic research support, especially for esteemed academic institutions, such as Princeton. These programs provide a mechanism for talented individuals to 'find each other and work together' which, according to participants, matches the emerging emphases of federal funding agencies on increasingly complex problems, such as the recent focus of the National Institutes of Health (NIH) on understanding and developing solutions for Alzheimer's and dementia.

While the NYU grand challenge program is also decentralized, its definition of success goes beyond receipt of federal grant funding; success is defined in terms of the implementation of specific grand challenge solutions to maximize their impact. For example, one team selected for the program is attempting to map the microbiome of New York City residents. The microbiome (or microbiotica) is the collection of organisms that live within our bodies and can play an important role in human digestive functions, among others. The effectiveness of applying lessons learned related to the microbiome relates to the extent that the team can work with outside partners, especially in industry, to develop solutions that utilize microbiota to, for example, improve digestion. Unfortunately, by the second phase of the study, the team was unable to attract partners or resources to develop further their ideas.

The success of the NAE Grand Challenge program is defined in terms of student academic achievement and the impact of required team projects undertaken in collaboration with faculty and community partners. A decentralized response occurs at two levels. First, engineering schools at universities such as ASU must adopt and integrate NAE guidelines into their academic

curricula.[10] Then at a second level, students must choose to participate in the optional curricular program. Once in, students respond to program guidelines by not only completing the engineering curriculum, they also work with other individuals to 'identify a project that directly relates to one of the 14 NAE grand challenges … it must fit within these areas and make an impact'.

The NAE program is credited with improving educational attainment and performance outcomes among women, minorities, and low-income individuals. However, study participants also spoke of challenges with the decentralized approach of the program. Students had difficulty connecting with individuals outside the university to serve as their community partners. For example, faculty at ASU help administer the program but do not possess the time or resources to build and maintain relationships with potential external partners on top of their other teaching and research responsibilities. The absence of what one participant calls 'a relationship infrastructure' means that:

> The projects are sub-optimal because we are having challenges connecting students with community partners, much less external experts who can help them figure out the technical aspects of the problem. Of course, we have folks that will work with us … but we need hundreds of partners, not a couple of dozen … how do you manage all that?

In other words, the impact of the program is constrained by the absence of an infrastructure that could enable participants (in this case, student–faculty partner teams) to scale their results.

The DARPA grand challenge competitions also employ a decentralized entrepreneurial response that is not only adaptive but also relatively inexpensive. Specifically, DARPA repeated and adjusted the grand challenge competitions between 2004 and 2007 to improve the development of AV technology and, later, reconfigured the competition (in 2012) to develop other autonomous technology use cases, such as the need to rapidly rescue individuals from natural or man-made disasters. In 2004, for example, the first DARPA grand challenge required participating teams to complete a 150-mile race course. While no team completed the 2004 competition, DARPA officials realized that '…[S]omething amazing was going on within the teams … and we didn't want to cut that short. We knew the teams needed a little more time and a little help … and the race generated all kinds of media attention and public interest.' DARPA leadership thus decided to repeat the challenge in 2005 and not only received double the number of entrance applications (196 in 2005 compared to 106 in 2004), but also saw four teams finish with a number of new innovations developed in the process. The 2007 competition simulated an urban environment replete with pedestrians, traffic stops, and traffic to spur further AV advancement.

However, in contrast to decentralized programs at NYU and ASU, DARPA's Grand Challenge participants are supported by a sophisticated developmental infrastructure associated with DARPA's long-standing relationship with mission agencies (e.g. Army, NASA) and

[10] According to the NAE, sixty-nine universities are part of the grand challenge scholars program. For additional information, see <http://www.engineeringchallenges.org/GrandChallengeScholarsProgram/15784.aspx> accessed 25 Mar 2019.

industry.[11] The grand challenges served as proof-of-concept motivating the relevant technology development arms of mission agencies, such as the Army's Tank Automotive Research and Development Center (TARDEC) and NASA's Jet Propulsion Laboratory, to work with participating teams and further develop AV technology for future augmentation into military and space missions. In order words, the decentralized approach of the DARPA grand challenges fits into a broader public strategy and support infrastructure for generating radical innovations and developing them to fulfill public missions.

Other programs respond to the recognition of opportunities through centralized governance mechanisms, that is, when grand challenge programs themselves lead and organize entrepreneurial responses. According to study participants, strong, centralized programs are needed when grand challenges require a long-term commitment not otherwise fulfilled by governments or market forces. For example, representatives from USAID spoke of their inability to convince traditional international development contractors to develop sustainable energy solutions for communities in poor, rural regions around the world, especially Africa: 'Many of the organizations we rely upon to implement on-the-ground solutions didn't want to invest in the energy-related capabilities they needed to undertake this project … we found out that other development agencies had similar experiences and that became the basis for our "Powering Agriculture" grand challenges initiative.'

Early ideas for the USAID grand challenge project emerged in 2009 during discussions with the Swedish International Development Cooperation Agency (SIDA) relating to areas of common interest and programming. The German Federal Ministry for Economic Cooperation and Development later joined. Further, the partners enlisted the help of Duke Energy, a large US power company that had been developing solutions for farmers located in rural agricultural regions of the USA, but who otherwise had limited experience in international development. The long-term commitment of the development agencies enabled Duke Energy to commit its alternative energy capabilities to the project thus making implementation and scale possible.

In contrast, representatives from the BMGF spoke of how their program's early commitment to exclude the pharmaceutical industry from their vaccine development efforts for the developing world unnecessarily constrained their ability to adapt. While the BMGF correctly viewed vaccine development as both a market and public value failure, they assumed that the pharmaceutical industry was partially at fault and that the BMGF could itself independently build internal vaccine development capabilities. According to a program representative:

> It took us years to learn that vaccine development is far more difficult than we anticipated. By not partnering with industry, we failed to understand their capabilities … their expertise in developing vaccines for domestic [US and European] markets … and how difficult it is to find individuals who understand various aspects of development … the science of disease, development vaccines, clinical trials, the regulatory process, manufacturing, and getting it to the populations. This attitude changed over time … hiring people from industry and working with companies has helped us understand

[11] For a discussion of DARPA's broader role in the development of modern innovations and their corresponding industries, such as computing, advanced materials, and the Internet, see Bonvillian (2014), Fuchs (2010), and Van Atta (2008).

> regulatory and manufacturing processes and some of these companies have become our largest source of in-kind donations … promising vaccines that they otherwise do not have the time or resources to develop.

In other words, program success depends on the ability for centralized grand challenge programs to connect over time with partners that advance their solutions.

The capability to manage partner engagement must also be thought of dynamically: grand challenge programs must possess the capability to recruit new partners, just as other partners may choose to leave, based on availability, resources, and grand challenge program needs. For example, USAID led a grand challenge program that sought to develop disease-resistant crops for cultivation within arid regions around the world. The project involved forty-three partners in eleven countries over five years. Early partners focused on genetic coding, while other partners joined to breed and test multiple hybrids. Other partners worked with farmers within specific regions to understand their specific needs and contextual issues that have affected the effectiveness of their efforts.

Representatives from Grand Challenges Canada spoke of how their centralized response enabled coordination among the other grand challenge programs involved in vaccine development (i.e. BMGF and USAID). The close working relationship among the centralized programs stems from the fact that the establishment of Grand Challenges Canada and USAID were heavily influenced and aided by the BMGF. The three programs have thus differentiated and coordinated their specific roles in vaccine development. The BMGF has focused on improving technical and manufacturing aspects of vaccines through their product development partnership program, while Grand Challenges Canada has sought to develop innovations to improve vaccine supply chains, and USAID has focused on ways to improve administration of vaccines and reduce associated cultural barriers. By focusing on specific aspects of vaccine development, these lead organizations have also attracted additional resources from other governments around the world.

Analogous to DARPA efforts to understand and support the technical needs of competition participants, the study uncovered examples of centralized programs developing the capabilities of program partners. For example, the BMGF worked with the US Food and Drug Administration (FDA) to help the Serum Institute of India to develop flexible and responsive vaccine manufacturing capabilities. The Serum Institute has since become the only location outside of the USA and Europe that conforms to the FDA's strict drug manufacturing standards and can quickly adapt its vaccine manufacturing lines in response to the emergence of rapid disease outbreaks such as poliovirus in Pakistan or Ebola in West Africa. USAID and SIDA similarly provide training to individuals from Duke Power as well as local partners in Africa involved in the Power Agriculture initiative to improve their ability to implement program solutions.

Though the Smithsonian Institution grand challenge program operates at a different scale than the centralized programs mentioned above, success is nonetheless enabled by a program office that seeks to scale the impact of participant projects. The Smithsonian's grand challenge program was initially established to continually improve the experiences of visitors to Smithsonian's dozens of museums and other cultural landmarks. It initially did this by encouraging Smithsonian

staff to work together to create innovative new exhibitions and research projects that would become the basis for future exhibitions. As the program evolved, program coordinators realized that participants were collaborating with hundreds of researchers, artists, and citizens all over the world, including peer institutions in other countries. However, according to an official:

> We realized that we couldn't keep track of everything that was going on … we knew that many staff were working with the same people at the Louvre or Acropolis Museum but we struggled to people who could help us develop really new ideas about [for example] the American experience … Think of how opioids affects society today … how do we find the right individuals that help us understand the use of opium around the world and over time … legitimate and illicit uses … smuggling and trade that goes back hundreds of years?

In response, the program expanded the size and role of staff who could enable individuals to focus on developing further their ideas while helping them establish and maintain relationships with new experts and institutions outside of the Smithsonian who could enrich their projects.

5. Discussion and implications

This study investigates *how* grand challenge programs evolve over time in response to rapidly-changing problems and contexts. It focuses specifically on governance mechanisms that identify and select target problems as well as implement related solutions. According to study participants, the impact of grand challenge programs is dependent on their capacity to adapt—what we term *adaptive capabilities*—to evolving problems and contexts in which their programs operate.[12] Adaptive capabilities include inter-organizational governance structures that enable the monitoring and analysis of grand challenge problems as well as mechanisms for program implementation.

Table 3. Taxonomy of decision structures for grand challenge programs

	Participant definition of the problem	**Top-down definition of the problem**
Decentralized implementation of problem solutions	• ASU • NYU	• DARPA • Belmont Forum • NAE • Princeton
Centralized implementation of problem solutions	Smithsonian Institution	• BMGF • Grand Challenges Canada • USAID

Illustrated in Table 3, some programs (i.e. ASU, NYU, Smithsonian) provide autonomy to program participants to identify specific problems of interest, while other programs (i.e. BMGF, Grand Challenges Canada, USAID, and Belmont Forum) possess mechanisms to define specific

[12] We draw conceptual inspiration from dynamic capabilities, an organization's ability to adapt and maximize its impact within rapidly changing environments (Helfat et al. 2007). Relevant to university-based grand challenge programs, Hayter and Cahoy (2018) employ the dynamic capabilities to describe how colleges and universities can strategically fulfill their social responsibilities. Further, Kuhlman and Rip (2018: 452) discuss the importance of capability and capacity building in the function of grand challenge programs.

problems and subproblems—or articulate broad, directional problems within which program participants can focus on specific subproblems therein (i.e. DARPA, NAE, Princeton). Further, programs differ in the extent to which grand challenge programs lead the implementation and scale of solutions, from a centralized response (i.e. BMGF, Grand Challenges Canada, USAID, Smithsonian) to decentralized responses (i.e. ASU, Belmont Forum, NAE, NYU, Princeton). Following Modic and Feldman (2017), centralized and decentralized governance mechanisms are important for explaining program success, in this case, how specific adaptive capabilities are deployed in response to differing circumstances.

Programs that enable participants to define problems can identify unique challenges as well as innovative solutions that might be otherwise neglected by a top-down approach. Decentralized organizational approaches seem to be particularly well suited when the goals of the program are relatively modest (e.g. motivating compelling student projects). The approach is also valuable if the program defines broad directional categories (e.g. the advancement of human health research [Princeton]) but relies on participants to meet well-articulated program goals (e.g. increase the number and size of NIH-funded research grants). However, when project goals are more ambitious, such as NYU's goal to generate an impact for the people of New York, a decentralized approach to program implementation is, according to respondents, less effective.

When participants defined their solutions in an open-ended manner (NYU) or within the context of a broad technology (DARPA), a governance infrastructure or ecosystem enables participants to develop further and scale their solutions. While a robust infrastructure does not exist for NYU participants, the Smithsonian supports the implementation of ideas among its participants through a small program staff that has the ability to assume various project management functions, such as relationship management and grant writing. DARPA defines program goals but relies upon participants to determine how they will meet these goals and subsequently develop and scale their ideas. DARPA helps connect program participants, however, with other government agencies and private sector organizations which can support their future development.

Some programs possess *ad hoc* or standing mechanisms that clearly define and update their grand challenge problems and lead the implementation response (i.e. BMGF and Grand Challenges Canada). Along with USAID, BMGF and Grand Challenges Canada assume that connecting top-down problem definition to a centralized implementation approach is critical to generating scale in the context of complex, trans-national problems. Thus, these programs clearly defined grand challenge problems and subproblems to create focus to build technical communities of practice, enable long-term partner commitment, and attract additional funding.

However, programs that centralize both problem definition and implementation functions are vulnerable to shifting problems if they do not possess robust adaptive capabilities. In addition to the aforementioned *ad hoc* or standing capabilities to understand the changing nature of problem, adaptive capabilities also include the capacity to manage the dynamic entrance, performance, and exit of partners based on program needs. Viewing partnerships dynamically and strategically also allows grand challenge programs to coordinate responses among other centralized partners and thus maximize their collective impact. Finally, grand challenge programs can help program

partners build their own internal adaptive capabilities so they can enable the overall program to be more responsive.

Several implications for policymakers interested in establishing grand challenge programs follow from our study. While funding data were unavailable across all programs, differences exist in financial resources available to programs in the study were evident. Available resources range from the initial $200 million grant (and subsequent funding) by the BMGF, to the approximately $1 million used to organize the 2004 DARPA Grand Challenge (no team finished the race and thus did not claim the available cash prize), to the modest NAE program, the implementation of which has occurred at ASU (among other universities) through the volunteering efforts of dedicated engineering faculty and one part-time program coordinator.

Despite these funding differences, it is worth reiterating that the primary purpose of grand challenge programs is to encourage solution-oriented collaboration—that is, generating innovative new solutions to complex problems and implementing these solutions at scale—a goal that can be realized in a variety of contexts.[13] While, following Eisenhardt et al. (2016), 'one size fits all' recommendations are likely counterproductive, this study yields practice-oriented insights that are valuable for public entrepreneurs: managers and policymakers who have established or are interested in establishing and operating grand challenge initiatives of their own. We articulate several related organizational considerations below, including program purpose, problem scope, temporal aspects, and partner capabilities and explain how each facet relates to grand challenge program establishment and operation.

While all programs in the study were motivated by various grand challenge problems, the purpose of these programs differed widely. Many programs are established to help *solve* a specific grand challenge problem. For example, the BMGF program was established to fulfill the principals' desire to improve the health of children in poor countries. In contrast, the primary purpose of the NAE (and ASU affiliate) is the development of collaboration and problem-solving skills among engineering students by using grand challenge problems as a motivating medium. Goals can also be differentiated temporally: the short-term goal of the Princeton program is to increase the number and size of research grants, while the long-term goal is to foster a culture of collaborative problem-solving in an environment where scientists from different disciplines may not otherwise have incentive to work together.

Program goals thus help determine how problems are defined. Programs that seek to improve education and generate out-of-the-box ideas should enable some autonomy to define problems and derivative solutions. However, if the goal is to solve a specific problem, then the program should itself narrow the program focus (e.g. AVs) or articulate specific program goals (e.g. the development of an AIDS vaccine) and develop the capability to understand the changing nature of problems and accordingly adjust the goals of the program over time.

Further, if problem-solving is the goal of the program, then a related consideration is problem scope. Though both efforts address important social goals, developing vaccines for diseases that

[13] Modic and Feldman (2017: 447) similarly posit 'But more than the dollar amount of funding, it is clear that the organization and implementation of these Grand Challenge projects will play a significant role in determining their ultimate outcome'.

disproportionately affect poor nations is more complex and ambitious than creating intriguing new museum exhibits. Thus, grand challenge programs that seek to solve complex, global problems must possess the capacity to attract significant resources, technical capabilities, and the governance mechanisms to support its goals over long periods of time. While these requirements are likely to be a barrier to entry for all but well-resourced governments and large foundations, future solution-oriented grand challenge programs should articulate a problem scope that fits with what can be reasonably achieved. For example, land conservation (Tang and Tang 2014) and watershed management (Koontz and Newig 2014) efforts discussed in the governance literature showcase the opportunity to collaboratively address local or regional problems not otherwise illustrated in this study.

Related to both purpose and scope, temporal factors should be considered during program design and operation. If the primary program goal is to solve a problem of expansive scope, programs should view implementation as a centralized endeavor guided by the aforementioned adaptive capabilities. If the goal is to provide students with problem-solving and collaboration skills, specific interventions might range from a day-long collaboration workshop to year-long team projects that are nonetheless finite in duration. Programs can also be organized annually (Princeton), periodically based on stakeholder interest (Belmont Forum), or as a one-time pilot event that might not be repeated depending on resources and interest (NYU)—or is continued and modified based on enthusiastic participant responses and the fulfillment of initial program objectives (DARPA).

Another important consideration is the technical and organizational capability of participants. As discussed above, the dynamic management of partner relationships is a critical adaptive capability, one that should be guided by an understanding of participant capabilities. For programs that centrally define problems and implement solutions, partners are recruited and managed by their capability to directly contribute to program goals. These partners may require assistance to understand contextual aspects of the program (i.e. helping Duke Power understand agriculture in Africa) or to approve their respective adaptive capabilities (i.e. Serum Institute). However, for the Smithsonian, DARPA, and Princeton programs, participants are likely more knowledgeable about the technical aspects of the solution than the program hosts, yet may lack the organizational or project management capabilities to implement and scale their solution. An understanding of partner capabilities should thus drive managerial decisions about how to best support efforts to develop and scale their specific solutions.

It is also important to understand the relationship between a host organization and how a grand challenge program is designed and deployed. For example, DARPA's grand challenge program uniquely supports the agency's mission of developing radical, new technologies to meet the strategic needs of the DOD—and perhaps form the basis of new industries (e.g. AVs). The program accomplishes this by constituting and reconstituting unique groups of participants to build new technical communities and accelerate technology development among existing communities, goals dependent on an understanding of partner capabilities and temporal aspects of the technology of interest. While the program is not viewed as a 'permanent fixture', it fits DARPA's overall decentralized, network-based structure; DARPA has decades of experience fostering what Colatat (2015) calls collaborator novelty. New mixes of collaborators, with the

support of the aforementioned developmental ecosystem, collectively develop new, revolutionary innovations.

Of course, DARPA's mission, history, resources, and evolution differ substantially from research universities, philanthropic foundations, social institutions, or other organizations not otherwise discussed in this study (e.g. municipalities, sub-national governments, corporate foundations). The broader point of this study, however, is that a tension exists between the two primary goals of grand challenge programs: defining problems and generating solutions to complex challenges in society and the implementation of these solutions at scale. Thus, in addition to its conceptual contribution, this article provides the considerations above to guide the establishment and operation of future grand challenge programs that address various societal problems and goals, contexts, and resource conditions. Our hope is that future research will empirically refine and expand upon these considerations.

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