Science Policy Research Report:
The Use of Innovation Prizes in Government

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Abstract

Prizes – competitions that offer a reward to the first person or team that achieves a certain feat or solves a specific problem – can play an important role in science, technology and innovation policy. Through innovation, they could help countries tackle and solve complex problems to achieve important goals such as becoming more competitive, advancing the national health, and securing the national defense. Given the growing interest in this incentive mechanism, its potential to induce notable effects and the uncertainty it generally involves, there is a need for a systematic compilation of scientific knowledge on how to design, manage, and evaluate prize programs.

This report presents the result of a synthesis that analyzes existing empirical evidence on prizes and provides ideas and actionable recommendations to help government agencies make a more effective use of prizes and achieve their missions. Prizes represent not only unconventional instances of innovation and creativity but also opportunities to, for example, educate and train students in science and technology and increase awareness of broader policy issues. Therefore, while the aim of this synthesis is a better understanding of the value and potential of prizes for innovation, its recommendations also relate to the search for solutions to other pressing societal or economic problems that are not necessarily technology-related.

The synthesis evaluates empirical scholarly works of the past 15 years and then reviews this evidence to clarify what is and what is not known about prizes with regards to their use in science and technology policy. It seeks to answer questions such as how certain design parameters affect their outcome, the actual incentive effect induced per award dollar, and the kind of contributions prizes make to their sponsor's mission. The findings of previous U.S. National Science Foundation's Science of Science and Innovation Policy-funded prize research provided the seed knowledge to start the synthesis and focus on five main themes: the appropriate opportunity to use prizes, their design, governance, outcome and evaluation. The synthesis also elaborates on the methodological quality of the source literature and seeks to understand differences across studies.

1. Introduction

This report synthesizes scientific evidence and seeks to summarize and clarify what is known and what is not known about innovation prizes. The growing interest, number of federal government competitions and budget allocated to these initiatives have led to more sophisticated prize programs involving partners, more ambitious goals and more diverse applications. Moreover, the initiatives to make prizes a standard tool to promote innovation at every federal agency accumulated valuable practical experience but did not lead to a systematic, more comprehensive evidence-based understanding of prizes. From a more abstract perspective, the uncertainty involved in the prize phenomenon also emphasizes the need for more systematic knowledge to reduce the cost and risk of launching new prize competitions.

Prizes are incentives that have long been used by public and private sponsors to elicit effort of individuals and organizations to accomplish diverse goals. In recent years, scholars and prize advocates have increasingly called attention to the potential of prizes to induce technological innovation and accomplish broader economic and societal goals. In U.S. policy circles, government prizes have been re-discovered after well-publicized private prizes (such as the Ansari X Prize) were announced in the mid-nineties and in the context of the emergence of broader initiatives and new concepts such as that of *grand challenges* in science, technology and innovation policy. Based on this short experience, the federal government has considered prizes "a proven way to increase innovation for the public, private, and philanthropic sectors" and sought to make them an important component of the portfolio of policy instruments available to agencies. This only stressed the need for empirical research to design, conduct, and evaluate prize competitions.

Still, considering the interest in and popularity of prizes, the body of empirical literature on prizes is remarkably limited. This synthesis found only 23 academic empirical works on prizes published in the past 15 years. Works that focus specifically on government prizes are notably scarce – only 11 works out of 23 are of this kind. Moreover, only a handful of publications have introduced and/or probed models and constructs and no research has tapped into that fundamental knowledge to investigate other types of prizes or prize applications. One of the most striking findings is the lack of original datasets or primary data sources, highlighting the need for more and more robust data collection. Many questions whose answers would be valuable to inform government prize design remain unanswered.

The systematic evaluation of this small body of empirical literature is however challenging due to its diverse perspectives to the topic and a lack of more overlaps that could enable comparisons. Therefore, we set out to address five main, broadly defined themes (namely: opportunity, design, governance, outcome, and evaluation) and also identify topics that have not been yet investigated. We link these "unknowns" to two research thrusts that scholars should pursue, being the first of them – aimed at theory building – the most important. We find that prize evaluation is the big missing theme in the empirical literature.

Overall, we consider the existing empirical evidence valuable but still insufficient to inform objective-driven prize design. The questions we sought to answer – such as how certain design parameters affect the outcome of prizes, the actual incentive effect induced per award dollar, and the kind of contributions prize outcomes make to the sponsor's

mission – are crucial to fully understand this kind of incentive mechanism. Yet, our synthesis found partial answers to those questions and only some insights to offer basic ideas and actionable recommendations. We hope the latter will still help inform decision-making and make a more efficient allocation of scarce scientific resources in prize programs.

The rest of the report is organized as follows. Section 2 discusses some conceptual aspects and the recent use of prizes in government. Section 3 describes the methodology and data of this synthesis and general findings on the body of empirical literature. Section 4 presents a synthesis of the empirical evidence along with ideas for government prize sponsors. Section 5 discusses findings and provides further research recommendations, and Section 6 presents concluding remarks. Along with each finding, this report offers actionable ideas and recommendations for government prize sponsors and, at the end, considerations for future policy implementation and research.

2. The use of prizes in government

Prizes are incentives that have long been used by public and private sponsors to elicit effort of individuals and organizations to accomplish diverse goals, including the promotion of science & technology (S&T) and innovation. In the 18th century, for instance, scientific societies used prizes to encourage basic research by compensating research results with monetary rewards or medals. Private sponsors also used prizes to incentivize the initial development of the aviation industry in the early 20th century. Notable prizes in history include, for example, the government-sponsored prize offered by the British Parliament in 1714 to the first person to invent an instrument for accurately measuring longitude at sea, and the privately funded Orteig Prize for the first aviator to fly nonstop from New York to Paris (won in 1927 by Charles Lindbergh).

Scholars and prize advocates have used the terms "prize", "contest", and "grand challenge" interchangeably and in diverse contexts.[1] Herein, these terms refer to incentives provided in the form of competitions that offer a reward to the first entrant to solve a certain problem through technology development or to some other form of technology-related achievement. More importantly, we look at these prizes from a policy instrument perspective, which distinguishes them from various other forms of prizes increasingly used by companies and other private entities.

More specifically, the innovation prizes or *grand challenges* discussed in this report define a problem ex-ante and seek to source a more creative, affordable, or efficient way to solve such a problem (that is, the sponsor is not just sourcing an idea). Prize problems are generally ambitious, tackle significant issues and may involve significant research and development (R&D) efforts. The media and the public generally recognize these prizes because they offer sizable monetary rewards and can become a large-scale (some

[1] Other forms of contest not discussed in this synthesis include: online community-based idea contests; internal contests and employee ideation contests; crowd-based innovation processes; open idea competitions; open innovation platforms; open innovation tournaments; innovation "jams"; creativity contests; employee suggestion systems; creativity and innovation ex-post awards; business plan competitions, and tournaments theoretically modeled. The synthesis does not address advanced market/purchase commitments as a form of reward either.

times global) effort. As we discuss later on, these prizes greatly depend on existing technology, ongoing R&D efforts, and information diffusion to attract participants and spectators as well. Private entities such as The X Prize Foundation but also U.S. government agencies such as NASA and DARPA have made this kind of prizes popular. Furthermore, Challenge.gov - the official hub or platform for U.S. federal prize and challenge competitions – has been also modeled after this kind of prizes (Murray et al., 2012).

Considering the variety of prizes and awards covered by the literature and the unique features of the prizes addressed here, conceptual distinctions apply. These prizes are not "ideation" contests because they generally require or make necessary to build and/or further develop technology to be able to accomplish the feat, solve the problem and claim the reward. However, they generally are technology-neutral, that is, they do not require the use of any specific approach or technology. These prizes are not "science awards" such as those given for progress made in sciences and engineering, when a panel of experts determines ex-post who the winner is (e.g. Nobel Prize). They are not procurement mechanisms or "mandatory" prizes either, such as those existing in bids for government contracts (Williams, 2012). Finally, this report focuses on government prizes, which share some features with "open innovation" approaches led by companies but differ in a number of aspects because of their different goals.

In recent years, scholars and prize advocates have increasingly called attention to the potential of prizes to induce technological innovation and accomplish broader economic and societal goals (see, for example, Kalil, 2006; Rimmer, 2011; Wagner, 2011; Everett et al., 2012; Goldhammer et al., 2014). Modern prizes successfully captured the attention of the public and the media and demonstrated technological possibilities through significant achievements. The $10 million Ansari X Prize, for example, announced by The X Prize Foundation in 1996, involved the development and launch of a reusable manned spacecraft into space, highlighting privately led commercial space development activities. Meanwhile, in government, prizes such as the $6.5 million given by the U.S. Department of Defense's DARPA Grand Challenges are associated with extraordinary technological achievements in the development of autonomous robotic vehicles.

To date, however, despite valuable prize experience and growing interest, there still is little empirical scientific knowledge on how to design, manage, and evaluate these competitions[2] and much of what we know about the societal, economic and technological effect of prizes is not the result of robust and reliable scientific research.[3] Moreover, prizes have been used in such a range of contexts and aiming at such a range of purposes that a better understanding of their effect and potential requires considering factors such as prize type, sponsor goals, reward structure, geographic coverage, and criteria to find a winner, among others. For instance, while some innovation prizes aimed at inducing R&D activity on specific technology to accomplish the mission of government agencies (e.g. NASA's Centennial Challenges to develop vertical take off and landing vehicles for

[2] As a reference, Murray et al. (2012) pointed out that, as of that year, there were only two empirical works on prizes: Brunt et al. (2012) and Kay (2011a).

[3] For example, a series of reports on The America COMPETES Act illustrate the effect of prizes with a number of success cases and achievements of the Challenge.gov program, which has had, as of October 2015, more than 450 challenges. To date, according to the data available to this synthesis, only two empirical works tapped into the data generated by such a program to answer questions on the design, implementation and evaluation of prize competitions.

manned space exploration) others have focused on commercial development of new industry sectors (e.g. Ansari X Prize).

The predominant rationale for the use of prizes in the scholarly literature relates to theoretical opportunities for prizes to perform better than traditional incentives such as patents and grants (see more in, for example, Williams, 2012). Yet, while theoretical works have thoroughly modeled and discussed diverse prize architectures and their economic benefits compared to *alternative* incentives, recent government prize programs do not replace patents or grants. Competitions such as NASA's Centennial Challenges and others in Challenge.gov are actually associated with post-prize grant opportunities, procurement contracts and the possibility for entrants to patent their technology.[4]

In a different line of research, other literature – including some that adopted econometric analysis – started considering patents and prizes complementary in a number of ways. For example, patents could help promote subsequent technology development after a prize program (see, for example, Davis & Davis, 2004; Brunt et al., 2012). A number of empirical works also investigated other notable features of prizes, such as the effect of non-monetary rewards and the participation of groups of solvers with a wide range of motivations. Yet, overall, this literature has only partially investigated prizes and has failed to develop prize theories and models to, for example, justify America COMPETES Act-style innovation prizes (Burstein & Murray, 2016).

In U.S. policy circles, government prizes have been re-discovered after well-publicized private prizes were announced in the mid-nineties and in the context of the emergence of broader initiatives and new concepts such as that of *grand challenges*[5] in U.S. science, technology and innovation policy (Williams, 2012; Furman, 2013; Hicks, 2016). The dynamism and broadly publicized advances of those modern competitions suggested exciting opportunities to use prizes to tap into widely distributed knowledge and induce collaborative efforts to address critical issues, including technological innovation. This drew the attention of policy-makers and sparked further discussion between government stakeholders and scholars.

In the second half of the 1990s, scholars and policy-makers formed a number of commissions and organized workshops to discuss the use of prizes in government and concrete applications (see, for example, NAE, 1999; Aldridge, 2004; NRC, 2007). They addressed topics such as amounts of prize rewards, more appropriate areas to conduct prizes, and types of rules and regulations that could be introduced in the prize process, yet without any reference to the still nascent empirical research. Only one of those reports, which discussed the experimental use of prizes at the National Science Foundation (NRC, 2007), addressed specific prize implementation issues such as early termination of contests and the appeal of award decisions. Overall, no empirical evidence backed these recommendations to support prizes in government and the prevailing rationale was based on the success of the aforementioned privately held prize competitions. Moreover, these commissions did not call for more empirical research on innovation prizes – they simply suggested pursuing experimental prize programs.

Interestingly, U.S. government agencies such as NASA and DARPA – likely the most active users of the government prizes we are interested in – started using these incentives as early as in 2004, when no specific legislation was still in place. It was actually not

[4] The toolkit materials on Challenge.gov though do adopt the "prizes versus other instruments" perspective.
[5] In this case, "grand challenges" is a broader concept and not only a reference to prizes.

until 2010 that some federal legislation addressed the use of prizes and gave agencies authority to use them (see **Appendix A**, Timeline, and also Stine, 2009). As a response to the Obama administration making prizes a key part of its National Strategy for American Innovation in 2009, the America COMPETES Reauthorization Act of 2010 provided all federal agencies with broad authority to conduct prize competitions and made provisions for different aspects of prize design, implementation, and oversight (Burstein & Murray, 2016). Shortly after, the federal government issued a number of guidelines (e.g. Zients, 2010; Bershteyn & VanRoekel, 2011) to support agencies in the process of adopting this tool.

The U.S. federal government also launched its own prize platform, Challenge.gov, which centralizes most of the prizes conducted by government agencies. More than 80 federal agencies – sometimes in partnership with other organizations – awarded more than $150 million in prizes between 2010 and 2016 (Gustetic, 2015). Between 2011 and 2014, the number of prizes under the America COMPETES Reauthorization Act or other authorities was 235. Prize programs became more sophisticated and ambitious with sponsor agencies aiming at the most diverse goals, such as engaging stakeholders and forming communities of solvers, sourcing innovative ideas, educating the public, and solving concrete problems with new technology.

Based on this short experience, the U.S. federal government has considered prizes "a proven way to increase innovation for the public, private, and philanthropic sectors" (The White House, 2016). This importance of innovation prizes in the portfolio of S&T and innovation policy instruments emphasizes the need for empirical research to design, conduct, and evaluate prize competitions. The use of prizes in government is not without risks. As we further discuss in this report, the empirical scholarly literature offers still incomplete and some times inconclusive empirical evidence on the effect and mode of operation of prizes and limited actionable insights to design and conduct effective competitions.

3. Synthesis method

This synthesis involved searching for and reviewing scholarly literature and synthesizing empirical evidence to draw lessons and put forward actionable recommendations for the use of innovation prizes in government. It is rather explanatory and does not seek to make an argument in favor of (or against) prizes. It seeks to understand not only what we know and do not know about the prize phenomenon but also what kind of research led to the existing empirical evidence. In particular, we set out to address five main, broadly defined themes:

a) Opportunity: This theme refers to the decision of whether a prize is the appropriate instrument to address or solve a specific problem. It resembles the "Discover" phase and matches the *When should government agencies use prizes?* question of the materials posted on Challenge.gov.
b) Design: This theme refers to the decisions sponsors make upon the architecture and functioning of a prize. It comprises aspects such as the definition of the problem entrants need to solve to be able to claim the reward, the value of the monetary reward and other non-monetary incentives, the prize timeline, and the

criteria for entrant eligibility. This is a pre-challenge stage that starts after the decision to use a prize. It resembles the phase "Develop" in Challenge.gov and addresses the question *What is the appropriate design of a prize?*

c) Governance: This theme refers to the program management actions sponsors need to undertake during the prize runtime period. It is equivalent to the "Challenge in progress, Conduct" phase in Challenge.gov and addresses the question *What should sponsors consider when running a prize?*
d) Outcome: This theme refers to both the immediate and long-term outcomes of prizes, the adoption of prize results, and other post-challenge effects. It is in part equivalent to the "Award" and "Transition" phases in Challenge.gov and addresses the general question *What is the outcome of prizes?*
e) Evaluation: This theme refers to works that apply evaluation methods to assess the content, implementation or impact of prize policies. It resembles sections of the Challenge.gov toolkit such as "5.1 Document Metrics, Results and Outcomes", "5.2 Document the Challenge", and "5.3 Complete Required Reporting". More generally, it addresses the question *How should sponsors evaluate prizes?*

We adopted a two-stage approach to gather empirical research literature published in the past 15 years. We started with the definition of an initial, pre-defined inclusion and exclusion criteria (Littell et al., 2008) that was applied to literature we gathered in our past projects (Kay, 2011a, 2011b, 2012a, 2012b; Conrad et al., 2017). This yielded 11 scholarly empirical works that became our "seed list". This seed list includes empirical scholarly works and meta analyses but not theoretical studies such as those that contribute abstract representations and econometric models of incentives and rewards in tournaments. In a second round, we sought to augment the initial set by reviewing citing works and searching for key prize-related terms (see **Appendix B**) on major databases such as Thomson Reuters Web of Science and Google Scholar. We also applied our empirical research criteria in this case. This second round yielded another 12 empirical works in various formats, including scholarly journal articles, academic working and conference papers, works published in book and book chapter formats, and policy reports written by academic researchers based on empirical studies.

This synthesis focuses on the set of 23 publications (hereafter, our "synthesis literature") that met our criteria of empirical research.[6] **Appendix C** of this synthesis includes the full list of data sources with key attributes such as year of publication, type of work, research design, data source type, research method, data collection and prize case study references. To complete our work, set the context of our discussion, and provide recommendations, we also reviewed the Challenge.gov website's resource pages and drew on other scholarly and non-academic literature that did not meet the empirical research criteria (the latter are cited throughout this report and included in our references list).

Our synthesis involved indexing, coding, analyzing, and writing this report. The analysis comprised an iterative process of tabulating, displaying, and cross-referencing data to assess the quality of research and strength of findings presented by the literature.

[6] Other scholars performed a more inclusive literature search and identified a larger number of academic works (see, for example, Adamczyk et al., 2012). Total counts of publications differ mainly because of the kinds of prizes and time periods addressed by the literature.

This helped discovering inconsistencies and knowledge claims based on multi-data source, more reliable evidence, among others. Qualitative text analysis software (QSR International's NVivo) and standard desktop computer software (Microsoft Excel) supported the analysis of literature and evidence, and the creation of an index and full reference list.

Our data gathering and pre-processing stages already offered a glimpse of this body of literature on prizes. While the literature discussed some forms of competition in government before our period of analysis (such as Rogerson, 1989, in defense procurement bids), it was only after the mid-nineties that scholars started paying attention to and publishing about the kind of prizes we focus on. A bibliometric analysis found that the "prize literature" broadly-defined (that is, including non-empirical literature such as prize proposals) is highly multi-disciplinary and includes scientific disciplines as diverse as agriculture, medicine, software, and aviation, among many others (Adamczyk et al., 2012). Since we focus on empirical research that addresses government innovation prizes, our list of references is more homogenous and generally has connection with economics, policy, innovation, and organizational studies. While our method is not bibliometric, we note that only a small number of works in our synthesis literature tap into each other's results and conclusions.

We classify this body of scholarly work on prizes into two broad groups: "Analysis" and "Synthesis". Analysis or *research works* are those designed as either qualitative or quantitative analytical inquiries that involve some form of primary data collection, hypothesis or proposition testing, and discussion of own evidence-based findings. This is the core set and includes the most robust research. On the other hand, *synthesis works* are those that draw on a number of (generally secondary) sources with explanatory or argumentative purposes, being in this case mostly arguments that favor the use of prizes by emphasizing either their advantages over other incentive mechanisms and policy instruments or their potential to generate certain benefits. There are actually a larger number of publications that synthesize other (often non-empirical) literature rather than original empirical work, but this synthesis discarded those that are mere commentary or unsystematic anecdotal accounts.

One of our most striking findings is the lack of a larger number of original prize datasets and primary data sources, which underscores the need for more robust empirical research. Moreover, there are only a few works that seek to build theory through the development of research constructs or the introduction and empirical probe of prize models. To our knowledge, only a few works (e.g. Mergel & Desouza, 2013, and Mergel et al., 2014) and no academic evaluations have looked into the Challenge.gov program as of the date of this synthesis. We also identified a number of key subtopics that have received little attention by scholars and discussed them in a **Discussion** section. We link these "unknowns" to two research thrusts that scholars should pursue, being the first of them – the most important – aimed at theory building. Evaluation is the theme that has received the least attention from scholars. Only one work of those reviewed here adopted an evaluative perspective (Burstein & Murray, 2016) yet using the privately sponsored Automotive X Prize case study (not a government prize). Another one offered more specific, albeit brief recommendations to conduct prize evaluations (Kay, 2011b).

We also reviewed the Challenge.gov website to search for references to our synthesis literature and reflect on practical aspects of prize design and implementation. We found a

significant amount of resources in slide/presentation, video and written article formats, generally authored by government officials with practical experience in prize execution. Yet, surprisingly, based on our review, the website does not include references to empirical academic literature.

There are different sources of empirical evidence on prizes (Table 1). We assessed the importance and considered the weaknesses of each type of source in the process of drawing lessons and crafting ideas and recommendations. The most valuable evidence is based on systematic direct observation of prize competitions, interviews with prize participants, and surveys of entrants. Evidence resulting from interviews with prize experts (i.e. those involved in prize programs) and industry informants (i.e. those that understand the technologies a prize deals with) is also important but potentially biased toward the prize sponsor interests or own technological approaches, respectively. Other evidence such as that resulting from documentary analysis – including online media and other prize literature – is also important but highly relative to its context for interpretation (it also is potentially unreliable and/or biased). In every case, we also consider potential issues of data coverage and assumptions made by scholars. For example, the empirical evidence resulting from the investigation of historical prizes refers to prizes held between the 17th century and mid-20th century. Modern prize competitions take place in a very different social, economic and technological context. Many conclusions drawn about historical prizes may not apply in the context of modern economies with a presence of much more developed markets, diverse forms of incentives, and innovation policies.

Table 1. Types of sources of empirical evidence on prizes

Type of source	Relative value	Potential issues	Select examples
Direct	High	• Ill-designed data gathering instruments • Coverage	• Participant observation • In-person or phone interviews with entrants • Questionnaires applied to/survey of entrants
Experts	Medium	• Response bias • Limited coverage	• Interviews with prize experts • Interviews with experts in prize technologies
Documentary	Medium/ Low	• Contextual influence • Reporting bias • Reliability • Limited coverage	• Non-academic literature • Online sources (e.g. an entrant's website) and social media • Historical accounts, stories by non-experts

Source: synthesis author.

There are a number of limitations to this study and approach. Compared to other non-academic literature, the reader may find that the ideas and recommendations that this report offers to sponsors are rather limited in scope and/or number. This is explained by the effort made to synthesize only the most robust empirical works and produce insights strictly based on conclusive evidence. Moreover, while comprehensiveness was one of the main goals of this synthesis effort, the primary focus was actually to tease out and synthesize the most valuable findings from the point of view of the quality of the research and the prize sponsor's general interest.

4. Empirical evidence and recommendations

4.1) When should government agencies use prizes?

4.1.1) Appropriate opportunities to use prizes depend on their focus along the process of technology development.

Prizes generally tap into existing knowledge and technology and reward further development. Evidence on the activity of entrants in recent aerospace competitions (such as the Google Lunar X Prize) and insights from industry experts show that prize entrants rely significantly on existing technologies and off-the-shelf components. In other words, some challenges may not be tackled if relevant technologies do not already exist or are not readily available to prize entrants (Davis & Davis, 2004; Kay, 2011a, 2012a). In a more abstract perspective, prizes may not work if they are offered "too early" along the process of development or are too ambitious for the current state of the art. For instance, a prize for market development would not be effective if the technology that entrants have to deal with is not commercialization-ready. Similarly, prizes for early stage technology development must consider whether some basic, enabling knowledge already exists.

Nevertheless, prizes might be able induce positive effects along the entire process of technology development. Kay (2012a), for example, based on the investigation of recent aerospace prizes and the technologies available to entrants, proposes four exemplar types of prize targets that agencies could aim for: research, proof of concept, development, and commercialization. Other scholars also define prize targets in similar terms. Masters (2006), for example, in a review of historical prizes, considers a prize for dissemination and adoption of new technologies in agriculture. Based on NASA's experience, Gustetic et al. (2015) also note the existence of matching prize categories. They define them in terms of objectives: attract new ideas, build prototypes and launch pilots, and stimulate markets.

There may be exceptions though. Liotard & Revest (2017), for instance, review Challenge.gov prizes and their most common use and conclude – albeit without evaluating the effectiveness of different types of prizes – that they appear more effective when they are held closer to research or early phases technology development (which in fact could be a matter of issues in technology adoption; see section **Outcome 4.4.7**).

The method to determine whether prizes are appropriate to tackle a specific problem in a certain sector is still unclear. This relates in part with the nature of prizes. They might involve diverse technologies and require a whole range of activities (e.g. not only technology research but also commercialization). The empirical evidence is not concrete in this regard, but it does highlight the need to consider prizes in the context of broader processes of technological development as further explained in this report.

Ideas for sponsors

✓ Use industry expert inputs and own prize experience to determine both what key technologies relate to a prize idea and their state of the art.

✓ Consider types of prizes based on their target along the process of development of the prize technologies as an organizing concept. For example: prizes for research, prizes for

technology development, and prizes for technology commercialization.

4.1.2) The economic context of competitions affects the effectiveness of prizes.

Expert and prize participant insights into recent competitions show that favorable economic contexts facilitate fundraising by prizes entrants. This suggests that prizes may not be as effective in opposite conditions such as economic slowdowns, particularly when prizes require significant R&D efforts to solve complex problems (Kay, 2011a, 2012a). However, the extent of the influence of the economic context on the ultimate effect of prizes in still unclear as competitions tap into widely distributed (even international or global) resources, there are diverse types of prizes, and the kinds of problems they target vary significantly.

Some scholars have a different perspective to the relationship between prizes and the economic context (see, for example, Liotard & Revest, 2017). Prizes, they argue, can have a potential positive effect on the economy through the creation of jobs and new companies (this is further discussed in section **Outcome 4.4.1**). Yet, these conclusions stem from limited evidence, such as case study reviews that find entrants who create a commercial enterprise after prize award, not a systematic analysis of this kind of output across multiple competitions. It is unclear how frequently this occurs and how this can become a more generalized effect on the economy.

Ideas for sponsors

✓ Gauge industry perceptions about current and future economic context and plans for R&D investment in sectors related to the prize technologies as a proxy to determine how favorable the context is to announce prize competitions.

✓ When announcing prizes that require significant R&D efforts in adverse economic contexts, consider offering additional support to entrants – financial or in-kind – to fund part of the activities to find a solution.

✓ In very adverse economic contexts, consider postponing prize announcements.

4.1.3) The most appropriate use of prizes depends on whether potential solutions are known and the availability of potential solvers.

The most appropriate use of prizes could depend of the information available to the sponsor about potential solutions to the prize problem and the size of the pool of potential solvers (in other words, prize opportunities still depend on the problem the sponsor wants to tackle and the technologies the prize deals with). Burstein & Murray (2016), for example, addressing the issue of prize governance and the government choice of innovation incentives, conducted a study of the recent Progressive Insurance Automotive X Prize case and concluded that prizes occupy a middle ground between traditional technology procurement mechanisms and patents. They argue that prizes, as in their case study, can be useful when the characteristics of the solution are not completely uncertain and there is likely to be a number of identifiable solvers who can provide such a solution (yet also, they clarify, room for unexpected or novel participation in the problem solving process). Masters (2006) studied a number of historical prizes – including the popular

early 20th century aviation prizes – and also concluded, more generally, that a prize is useful when the sponsor knows only the problem and is looking for information about what or who can best provide a solution.

Still, there is not a direct connection between the empirical evidence and the aforementioned conclusions, and drawing more concrete lessons to inform prize design is difficult. On the other hand, this literature considers prize and other incentives exclusive policy tools, which diverges, in part, with other empirical findings reported in this report.[7] Section **Opportunity 4.1.1**, for example, suggests that prizes have a wide range of applications across diverse technology sectors and are not necessarily an alternative to other incentives.

Interestingly, this perspective assimilates prizes to devices capable of obtaining information on potential solvers and technological possibilities. Yet, sponsors should have in mind that prize design elements – such as eligibility criteria for participation – also determine to some extent the types of entrants that will be attracted and engaged in competitions (see section **Design 4.2.2**).[8] In other words, there is some circularity in such an argument, and the information obtained on potential solvers could be biased because of the incentives offered by the very prize. Moreover, prize design and prize rule crafting require some knowledge on the potential solution to the prize problem ex-ante. The literature does not explain in more concrete terms what kind of information sponsors should have beforehand to be able to design effective prizes.

Ideas for sponsors

✓ Explore the technology landscape and consult with industry experts to learn about potential solutions to the prospective prize problem.

✓ Include pre-competition tests or qualifying rounds to obtain information on existing solver communities and the type of solutions they can contribute to tackle a specific problem.

- Lower entry barriers in initial rounds (or first prizes in the context of multi-prize programs) to attract as many participants as possible to obtain valuable information on the pool of solvers and potential solutions.
- Qualifying rounds can help filter out types of entrants that may not make significant contributions or are not up to the skills and capabilities needed to solve the challenge.

✓ Subsequent prizes or rounds could then be announced to tackle a more focused problem, possibly even describing the desired type of solution.

4.1.4) Phases of technology and industry sector development can affect the effectiveness of prizes.

[7] As a reference, readers should consider that the materials on the Challenge.gov website also explain prizes in terms of a choice between prizes and other more traditional incentives such as patents and grants.

[8] This emphasizes the importance of considering the interrelated nature of prize design factors. While sponsors can aim to attract as many and as diverse participants as possible, they can also design incentives to targets certain communities of interest. Openness in eligibility requirements still remains an important factor that allows participation of potential breakthrough innovators and helps obtain better information on the pool of potential solvers or communities that work on the technology (c.f. Masters, 2006.)

Phases of technology and industry sector development can affect the effectiveness of prizes through different means. One of these means is the "technology incentives" offered by potential or existing markets for the prize technologies, which, for example, have attracted entrants that seek to create a commercial enterprise in aerospace (Kay, 2011a, 2012a; Vrolijk & Szajnfarber, 2016) or incentivized entrants to partner with manufacturers in robotics (Nardi et al., 2016). More generally, prizes linked to potentially sizable markets are more attractive. Yet, as technology evolves, commercial markets and contract opportunities become relatively more important and also faster and more efficient at inducing innovation (Macauley, 2005; Masters, 2006, 2008; Masters & Delbecq, 2008). This is a matter of relative incentives though, and not an issue inherent to the prize mechanism.

Investigations into historical prizes also concluded that the incentive power of prizes can fade away as other incentives or funding mechanisms for innovation develop and become more prominent. For instance, Macauley (2005) notes that early 20th Century aviation prizes were very popular but their importance decreased later on as the aviation industry developed. Yet, on the positive side, scholars point out that industry development could have enabled competitions in sectors such as robotics (cf. Masters, 2006; Nardi et al., 2016). Masters (2008) also observed the presence of "bursts" in the use of prizes along a timeline of historical prizes and pointed out that those pockets of prize activity are connected with broader, favorable technological cycles.

While the evidence is generally compelling, the influence of contextual factors (e.g. international conflicts, economic slowdowns, introduction of other policies) on the effect of prizes is largely unexplained. In our literature dataset, we only found one attempt to introduce and probe a model that incorporates contextual aspects into the prize process, yet it was not further developed or tested in sectors other than aerospace (Kay, 2011a). The context is particularly relevant in the case of historical research, but it is unclear in historical prize case studies how they fit into the cycle of technology development and emergence of new markets on their time. In modern competitions, how both non-prize monetary and non-monetary incentives come into play along increasingly complex, globalized markets remains a fuzzy aspect.

Ideas for sponsors

✓ Consider three exemplar paths of prize program development according to the state of the art and the level of market development of the prize technologies:

- *Prizes for research, proof of concept and technology development* that focus on emerging technologies for which there are still no mature markets but the necessary basic knowledge and technologies already exist.
- *Prizes for technology commercialization, dissemination and adoption* focused on technologies already marketed.
- Other instruments for more mature technology markets.

4.1.5) Legal and regulatory constraints in government limit the scope of application of prizes.

New evidence on Challenge.gov prizes puts the decision about the appropriate use of prizes in a more practical context. Mergel et al. (2014) studied these prizes and found that

raising awareness about public issues – and not the provision of technical solutions – is the most common use of those prizes. They explain that legal and regulatory constraints in government agencies make prizes inadequate to source technologies.[9] In other words, prizes may not be suitable for developing new public goods and services, which generally result from political processes, Mergel et al. explain. Areas where the government typically uses private sector entities to source such goods and services, such as defense and aerospace, are the exception. This can explain why NASA and DARPA are among the few agencies that have used prizes for technical solutions. Both agencies generally tap into private contractors for technology procurement.

This evidence does not fully explain what the regulatory constraints are, but it reminds sponsors about the importance of legal and regulatory compliance. Sponsors should also consider that – as further explained in this report – raising awareness might actually be a general benefit of carefully crafted and well promoted prizes and, therefore, not an objective *per se*. Moreover, it is unclear whether Challenge.gov prizes reflect the most efficient use of prizes in government and of the platform itself (Mergel et al. only identify what the most common uses are). Other evidence presented in this report shows that prizes have multiple, diverse benefits and can also target specific objectives (see section **Outcome 4.4.2**).

Ideas for sponsors

✓ Discuss prize program ideas with legal counsels before launching a full-scale effort to use prize competitions.

✓ Consider not only the benefits and objectives of a prize program but also how to use and/or adopt the technologies developed in the context of prizes (see section **Outcome 4.4.5** and **Outcome 4.4.7**).

4.1.6) Prizes are better suited to address technology development areas for which patenting is not possible or is too expensive.

Prizes may have a particularly beneficial effect in areas where patenting is not possible or areas that have poor intellectual property (IP) protection. In other terms, prizes may be effective in technology sectors where no other incentives exist, where the knowledge created by market entrants cannot be appropriated through some form of IP protection, and/or where typical actors are individuals or small entities that cannot afford patenting costs.

Sponsors should consider that the empirical evidence and conclusions of scholars in this regard are based on historical research and is somewhat contradictory. For example, after the analysis of patenting activities by prize entrants, Brunt et al. (2012) point out that the steep cost of patenting in the U.K. may have led more inventors to enter prizes for agricultural development in the 18th Century. Khan (2015), however, in her analysis

[9] More specifically, about 40 per cent of the 203 prizes they surveyed focused on raising awareness. On the other hand, 53 per cent of all challenges initiated by science or defense-related agencies (such as NASA and DARPA) aimed at not only finding solutions to technical problems the agencies face but also raising awareness. Interestingly, as of the date of writing this report, the Challenge.gov toolkit explains that the purpose of prizes is to "entice innovators and support new market activity", not other purposes. More about this at: https://www.challenge.gov/toolkit/prepare-1_4/

of historical prizes in the U.S., U.K. and France, suggests that many of those prizes were actually won by ex-ante patentees and wealthy inventors.

Interestingly, after analyzing a diverse dataset of recent prizes in space, energy, health, among other sectors, Breannan et al. (2012) conclude that, compared to patents, prizes can play a role as an innovation incentive even when inventions do not meet IP law requirements, that is, inventions that are not novel, non-obvious, and industrially useful (this could also include the case of some technologies in the emerging domains of, for example, nanotechnology or synthetic biology, that might not meet traditional patenting requirements, we believe). Moreover, Breannan et al. add, the patent system cannot provide incentives just for solving the task alone, like prizes do.

It is worth noting that the literature does not provide any model of the relationship between prize incentives, IP, entrant strategic decisions, and technology markets. While both research and intuition suggest that a connection between access to IP protection and prizes exist, there is no concrete evidence on specific aspects such as the alleged effect of the cost of patenting on the strategic choice of prize entrants (see, for example, Davis & Davis, 2004).

Ideas for sponsors

✓ Survey the IP landscape of the sector that a prize will target to understand both factors that influence positively and hinder technological development and existing incentives (see section **Opportunity 4.1.1**); this could be particularly relevant in emerging sectors or technologies such as nanotechnology and synthetic biology, where technical disruptions also generate patentability issues.

✓ Use this survey to inform decisions of whether to retain the IP rights resulting from prize activity or make provisions for eventual licensing from prize entrants (see section **Governance 4.3.1**).

4.2) How does a "well designed" prize look like?

4.2.1) The appropriate combination of prize rewards (monetary and non-monetary) can maximize the efficacy of a prize.

Prizes are generally associated with a sizable cash purse that attracts the attention of the media and general public – it is a measure of the importance of the prize or how hard to solve the problem is.[10] Most of the literature that draws on econometric modeling to investigate incentives for innovation considers the cash purse the only prize incentive. Inexperienced commentators also, generally erroneously, consider the monetary reward the single most important item in a prize program budget (see section **Governance 4.3.3**). Possibly as a communication device, private prize sponsors have many times emphasized this by expressing the effect of prizes in terms of their multiplier effect or cash purse-to-entrant investment ratio.[11]

[10] Still, no research has addressed questions such as the correlation between prize monetary reward and media coverage.

[11] For example, an X Prize Foundation backgrounder document explains that prizes such as the Ansari X Prize produce a 10 times or greater return on the prize purse (X Prize Foundation, 2013).

Unluckily, there is no evidence-based insight into the appropriate method to determine what is an adequate cash reward in each case. Little evidence is connected to this, and it is inconclusive. For instance, while Macauley (2005) does not find any correlation between reward amounts and how challenging the problem tackled by the prize is, Kay (2011b) propose that the monetary reward should be a fraction of the potential costs of solving the prize problem. The remaining gap, he claims, induces other positive effects on the activity of entrants (see sections **Governance 4.3.1** and **Outcome 4.4.4**).

Moreover, scholars have barely addressed other designs such as monetary incentives in the form of progress payments or consolation prizes. Burton & Nicholas (2017) found that payments for milestone achievement played a key role to support the activity of entrants in the historical Longitude Prize. Similarly, Kay (2012a) points out that consolation prizes given for achievements that may or may not be directly related to the prize main goal – such as the Google Lunar X Prize's $1 million Diversity Award given to the team that makes the most significant effort to promote diversity in STEM fields – also play an incentivizing and supporting role. Yet, there is no evidence on how these incentives could affect the development of competitions if offered at inappropriate amounts or moments along the prize timeline (cf. Davis & Davis, 2004, on prizes that could potentially eliminate the incentive to continue innovating).

Non-monetary incentives linked to prizes, on the other hand, have increasingly received attention in the empirical literature. These incentives are connected to diverse motivations of prize entrants, which include, for example, their interest in publicity, reputation, prestige, and personal and professional challenges. For instance, the statistical analysis of a dataset of historical prizes for agricultural implements in the U.K. showed that medals had a positive effect in attracting entrants that was more significant than that of monetary rewards (Brunt et al., 2012). In recent aerospace prizes, entrants revealed diverse non-monetary motivations as well, including, for example, "participation in a real technical and intellectual challenge" as the prevailing reason to participate, as reported by 80 percent of Google Lunar X Prize entrants (Kay, 2012a). Some of these are intrinsic motivations and relate to personal traits of the participants, such as the opportunity that prizes offer them to accomplish a personal goal. Others are connected to professional and career opportunities such as the possibility to connect with like-minded professionals.

These insights suggest that a certain combination of prize incentives, monetary and non-monetary, can maximize the efficacy of a prize. Yet, the empirical evidence still does not explain a number of important aspects. More importantly, while there is a wide range of incentives sponsors can choose from to make prizes more effective, no research has offered a formula or method to determine their value and appropriate combination. In particular, there is no concrete evidence on the relative importance of each type of incentive, let alone on how these incentives can vary across types of prize, prize objectives, and technology sectors.

Moreover, more concrete empirical insights into how potential participants weigh their decisions to enter prizes against paths that involve other significant incentives – such as grants, contract opportunities and markets – would be very useful for prize design. For example, Kay (2011a) notes that, at least in space prizes such as the Ansari X Prize and the Northrop Grumman Lunar Lander Challenge, opportunities to commercialize the prize technologies is an important motivation for entrants.

Ideas for sponsors

✓ Define the prize cash purse in relative terms (e.g. prize as a percentage of the estimate on the cost of solving the problem) to be able to evaluate its importance as a determinant of the outcome of the prize program and inform future prize designs.

✓ Identify readily available non-monetary resources that could increase the value-added of prize participation, such as partnership and networking opportunities, prestige associated with the agency that sponsors the prize, and publicity that results from being part of a "cool" and potentially popular prize.

✓ Collect detailed information on prize entrant motivations so that incentives are adjusted in ongoing and future competitions.

4.2.2) Contestant motivation varies across types of entrants and over time as the competition unfolds.

The ability of prizes to attract diverse participation is one of their most interesting features. The response of prize entrants to very diverse motivations – not to a single prize incentive such as the cash purse – depending on their individual and organizational traits is an even more interesting fact. For instance, Vrolijk & Szajnfarber (2016) found that "platformers" or entrants who participated to expand upon or demonstrate pieces of their technology in some NASA prizes were driven by the market value of the technology and non-monetary incentives (rather than the monetary prize). Moreover, according to Kay (2012a), unconventional entrants in the Google Lunar X Prize – teams whose members had not been generally involved with the prize technology and could contribute fresh ideas – explain that their motivation relates mainly to non-monetary factors such as the opportunities for networking and participating challenging projects.

Scholars have sought to classify entrants with such diverse motivations into homogeneous groups. The ultimate goal of the participant and its experience with the prize technologies are examples of dimensions that define groups or *types* of entrants. This is very relevant for prize design because it implies that sponsors can target and attract specific communities or types of solvers by offering appropriate incentives. This also makes remarkable the little attention empirical research has paid to the classification of entrants and communities of solvers in innovation contests and their varying responses to incentives. The diversity in the perceived benefits of prizes (see also section **Outcome 4.4.2**) could actually explain the ability of prizes to attract such a diverse participation as well.

Moreover, incentives in long-term prizes or multi-prize programs could change over time. For example, different entrant cohorts – which existed due to a long registration period (longer than a year) – reported different motivations in the Google Lunar X Prize, in general and controlling for the level of experience participants had on the prize technology (Kay, 2012a). For example, within the group of "unconventional teams" (i.e. those not familiar with the prize technologies), while first year entrants were interested in technology commercialization, second year entrants were more interested in participating in a challenging project. A plausible explanation for this – Kay argues – is a competition that builds up momentum and offers varying opportunities over time. Similarly, this could explain the decisions to withdraw from competitions when the initial perceived benefits fade away.

The importance of this design aspect makes the existing evidence look insufficient. What is a proper taxonomy of entrants is among the most important questions to answer. The literature introduced mono-dimensional classifications that could be an oversimplification. For example, Kay (2012a) suggested that the ultimate goal of the prize entrants makes them weigh the prize money differently (e.g. if the entrant's goal is to start a commercial enterprise, the prize money is relatively more important for it improves the bottom line of a business plan). Yet, intuition suggests other relevant dimensions, such as previous prize entries. Moreover, the ability to link specific incentives with types of entrants would provide answers to questions such as how important is the reputational value for a certain group of solvers or what type of incentives can maximize the external R&D investment in a competition. It would also help design prizes that do not overlap or, in other words, compete for the same pool of potential entrants and media attention (Kay, 2012b).

Ideas for sponsors

✓ Kick off the prize process discussing the incentives that could increase prize participation with existing communities of practice.

✓ Segment potential entrants based on one or more attributes, list the incentives the prize could offer, and seek to determine the importance of each incentive to accomplish the prize objective. For example:

- Prizes for research that engage the scientific community and citizen science groups, could offer incentives such as prestige and interesting problems to solve.
- Prizes for technology development that engage entrepreneurs and startups, could offer incentives such as cash purses and contract opportunities.
- Prizes for technology commercialization that engage startups and SMEs, could offer incentives such as publicity and be aligned with potential markets.

✓ Introduce flexibility in the design of incentives to, for example, offer additional incentives if a prize does not attract significant attention immediately after its announcement.

4.2.3) The definition of the prize's target problem determines its ability to induce incremental innovation or breakthroughs.

Both the technological feat that participants need to accomplish to be able to claim the prize and the time allowed for such an achievement define the prize's target problem or *prize challenge*. Prize rules may let entrants choose the means to solve a pre-defined problem, or expressly require developing some device, contraption or system that must perform according to certain parameters. Prizes may also reward the best performing team according to certain metrics. The target problem also aligns the prize, to some extent, with certain technology sectors and potential markets. Moreover, it determines the kind of skills, capabilities, and resources necessary for its accomplishment.

The potential for both incremental innovation and breakthroughs are connected in the literature – albeit still imprecisely – with the definition of the prize problem. On the one hand, series of increasingly difficult prizes and competitions that reward performance seem to be associated with incremental innovation. For example, Macauley (2005), in her study of early 20th Century aviation prizes, concluded that prizes, by making feats

increasingly difficult over the course of years, induced incremental progress and helped jumpstart the industry. Nardi et al. (2016) compared one-off competitions and multi-year competitions in robotics – such as the university/government-organized Australian UAV Challenge and the U.S. DARPA Challenges – and pointed out that, while the former have the advantage of novelty, the latter can build upon previous results incrementally.

On the other hand, technological breakthroughs could be associated with complex, bigger prize challenges. Recent aerospace prizes – such as the Ansari X Prize and NASA's Northrop Lunar Lander Challenge, for example – with ambitious yet doable challenges, with openly defined problem definitions as to allow innovation and creativity, led to incremental innovation but also novel approaches to problem solving (Kay, 2011b)., Moreover, a number of radical innovations have been attributed to X Prize Foundation's prizes and the definitions of the problems they sought to solve. Compared to traditional open innovation approaches that involve modularity and discrete, relatively small problems, these prizes tackled complex, broadly defined, systemic problems at once (Hossain & Kauranen, 2014).[12]

Prizes that pose challenging problems can also induce other positive effects. They attract, according to Kay (2012a), "unconventional innovators", who are willing to take risks and can contribute novel ideas and fresh approaches to problem solving. Moreover, technological targets that require significant funding can also lead to innovation in other aspects such as new business model development. For example, the kind of space mission required to win the Google Lunar X Prize may have positively influenced entrant activities due to its large budget and minimal resources offered up-front (Kay, 2012a).

Ideas for sponsors

✓ Use prize challenge specificity to narrow down or expand the solutions space:

- More precise challenge definitions can focus activity on certain types of solutions that sponsors are interested in.
- Ambiguous or open challenge definitions enable the comparison of diverse approaches to solve a problem (but also consider the downside, as described in sections **Design 4.2.4** and **Opportunity 4.1.3**).

✓ Use prize challenge difficulty to enable potential breakthroughs (posing big, complex problems) or incremental developments (targeting smaller, discrete problems).

Still, this is an aspect that emphasizes the need for a causal model that explains how specific design parameters lead to specific prize outcomes. This synthesis did not find such a model in the literature. This casts some doubt about the ability of prize sponsors to strategically design parameters such as the problem definition to induce certain outcomes (which could be impossible under certain conditions, as discussed in section **Design 4.2.4**). Moreover, once again, it is generally unclear, particularly in the case of historical studies, how technological and industry contextual factors relate to the problems

[12] According to Hossain & Kauranen (2014), this occurs thanks to some kind of self-organizing property of prizes in the process of gathering efforts and focusing them onto solving a big, systemic issue. This disputes the notion by which prizes can tackle just a "single, discrete invention goal" as much of the econometric modeling literature has considered (cf. Wright, 1983). As many prize advocates propose, prizes then could tackle complex problems such as global climate change or large-scale energy projects.

addressed by prizes and influence their outcomes. Finally, the effect observed on incremental innovation in multi-year competitions (cf. Nardi et al., 2016) contradicts in part other findings that suggest a fading effect of prizes over time (see section **Opportunity 4.1.4**). A potential interpretation is that, because of their fading effect over time, prizes would tend to induce only incremental improvements.

4.2.4) The problems tackled by prizes cannot be defined in terms of discrete, static dimensions.

Section **Design 4.2.3** rests on the assumption that prize sponsors can strategically define target problems to induce certain outcomes. This might not be actually possible, even if sponsors wanted to do so. Murray et al. (2012), after a thorough analysis of the Progressive Insurance Automotive X Prize case, conclude that some of the dimensions that defined the problem *"building viable, super fuel-efficient vehicles that give people more car choices and make a difference in their lives"* could neither be quantified nor anticipated, while other dimensions changed as the competition unfolded. Moreover, they conclude that there is no single, universal technical goal or metric that can describe such a prize challenge.

Fuzzy or changing definitions of the prize challenge could have significant implications for the use of prizes in government and their design. The most important implication possibly is the uncertainty introduced into the prize process, which could be reflected on confusing or ambiguous prize rules or criteria to determine the winning entry. In a worst-case scenario, this could make the prize program fail if potential entrants do not understand what they must accomplish to be able to claim the prize (and decide not to enter) or if current participants decide to withdraw upon changes in the original competition rules. Sponsors could also face legal issues as a result of this (Schooner & Castellano, 2015).

Ideas for sponsors

✓ Contemplate changes in industry technological possibilities that can outpace prizes or make solving prize challenges more difficult or unfeasible.

✓ Introduce provisions that anticipate those scenarios and seek to create metrics-based triggers to reduce subjectivity. For example:

- If technological capabilities do not seem to develop as fast as expected (e.g. by some measure of performance), extend the prize deadline.
- Declare competitions over if non-participant individuals or organizations solve problems similar to that of the prize.

✓ Use clear and concrete metrics of achievement; define them in relative terms to account for changes in technological possibilities and avoid changes in prize rules (e.g. the achievement required by the prize could be a measure of performance that duplicates an industry standard by the time of demo day).

Unfortunately, there is no evidence-based method to define prize targets, balancing openness with specificity based on the knowledge available to the sponsor on the prize technology and potential solutions. Moreover, the need for flexibility is a sound argument, but no hint is offered as to how sponsors should prepare to respond to

changing conditions (this is further discussed in section **Governance 4.3.2**). The metrics that would best measure achievement in different kinds of prizes would be another valuable evidence-based insight.

4.2.5) Panels of judges with external members increase awareness and interest in prizes.

Judge panels can guarantee fair competitions and reduce the possibility of conflicts when picking winners. Some evidence also suggests an interesting twist – making a strategic use of judge panels for both attracting more entrants and raising awareness about the prize purpose.

Based on a review of select Challenge.gov prizes and interviews with prize managers, Desouza (2012) recommends government prize managers to use external judges when the competition's goal is to engage a large number of citizens and obtain submissions with lower technological complexity. On the other hand, internal judges are best used when technical domain expertise in technologies related to the competition is necessary. For example, competitions such as the Department of Commerce's Business Apps included a judging panel comprised of notable people to attract a larger audience, while other prizes under the science and technology category such as the $50,000 U.S. Patent and Trademark Office's Algorithm Challenge have drawn on panels with internal judges because of the knowledge required to determine the winners in sophisticated technology applications (Desouza, 2012).

The little evidence on this strategic use of judge panels (and, particularly, a lack of evidence on cases that somehow failed because of non-strategic selection of prize judges) makes this design parameter less important than others. Moreover, while some literature has addressed topics such as fairness of review of prize submissions and dispute in government prizes (see, for example, Schooner & Castellano, 2015), no work has addressed this topic empirically or linked size and composition of judge panels to issues such as fairness in the process of awarding prizes, conflict resolution, and promotional efforts to disseminate the idea and purpose of the prize.

Ideas for sponsors

✓ Consider judge panels that include both internal field experts and external judges that are better known by the general public to help disseminate the idea of and raise awareness about the prize.

✓ Include external judges as long as this does not conflict with program budgets or the regulations that agencies have to abide by (the existing evidence does not raise any point with regards to the size of panels, such as the potential negative effect of having a numerous group on winner selection).

4.2.6) Regulatory and administrative processes prolong government prize design times.

Mergel & Desouza (2013) investigated the case of the Challenge.gov program and found that internal adjustments and vetting processes in government prizes (compared to privately organized prizes) take longer because of the public character of the platform. The Challenge.gov toolkit also suggests agencies to take into account how the timeline of development of prizes fits into the agency's plans and consider that private sector prize

examples may present a dynamism that cannot be achieved by government prizes. This evidence does not provide insights into how to streamline those processes to shorten prize design times.

Ideas for sponsors

✓ Consider prize competitions strategically in the context of the agency's long-term plans and the timeline of other programs and initiatives, even in the case of short-term prizes.

✓ Create a roadmap for technology and knowledge acquisition (or other program objectives) that maps prize activity and the activities of other programs of the agency.

4.3) What should sponsors consider when running a prize?

4.3.1) Prize entrant activities draw significantly on external resources.

Although prize sponsors only reward participants who find a solution to the prize problem, prize programs may induce costly activity, particularly in the case of ambitious competitions that involve solving complex problems. Some prizes support this activity through, for example, small milestone or partial achievement prizes or grants based on performance. However, this may not be enough to run a successful competition. Moreover, regardless of how well endowed a prize is, contestants always draw significantly on external resources (Masters, 2006). A literature survey suggests (based on literature subtopics) that prize entrants draw on diverse external resources – technological (e.g. off-the-shelf technologies), financial (e.g. investment), emotional (e.g. family support), and social (e.g. professional networks) (Adamczyk et al., 2012).

The evidence emphasizes the extent to which participants tap into external resources and how that could induce some interesting positive effects (Kay, 2011b, for example, notes that a lack of technological and financial resources can incentivize creativity). A survey of team composition of entrants in the Google Lunar X Prize showed, for example, teams with sizes ranging between 1 and 40 members that tapped significantly into volunteer effort, including friends, family, and students – more than 10 volunteers on average per team, with a team enrolling more than 80 volunteers (Kay, 2012a).

While the importance of these external resources is clear, the literature does not consider the uneven distribution of resources that could occur in some cases (that is, entrants with very different access to resources at the time of entering a contest). It also remains unclear, except for a handful of works that profiled prize entrants, how heterogeneous a group of entrants could be (i.e. resource-wise) and how that makes prizes more or less effective (or more or less exciting).

In any case, sponsors can adopt a facilitator role and help entrants raise funding or access other resources necessary to compete by providing, for example, equal access to software, laboratories, or office space. This may actually be necessary in prizes that involve problems that require significant funding to find a solution. Sponsors can also offer support in the form of progress payments for partial achievements or milestones (see, for example, Burton & Nicholas, 2017, on the Longitude prize case). Alternatively, participants can use the intellectual property they develop in competitions to generate

commercial opportunities and raise funding. Kay (2012a) argues that the importance of IP becomes higher in competitions that require significant investments. Moreover, this kind of asset can attract investment capital and lead to the formation of a commercial enterprise.[13]

A number of key aspects remain unknown to this synthesis, such as the value and importance of each type of resource ex-ante (so that they are considered in prize design), how the varying distribution of resources across entrants and uneven starting positions affect competitions, and if the latter requires actions to level the playing field. When it comes to the investigation into the effect of historical prizes, it is unclear how a very different context influenced the process of fundraising by prize entrants. Last but not least, the evidence on the effect of progress payments does not indicate whether external resources can supplant them.

Ideas for sponsors

✓ Facilitate access to resources through, for example, the search for partners that could support entrants (e.g. established brands, crowdfunding platforms) or the introduction of provisions that allow entrants keep the intellectual property they create in competitions.

✓ Support entrants through other means, monetary or in-kind. Monetary support includes, for example, progress payments or some form of grants to undertake R&D when prize problems have discrete definitions that can be split into modules (or unique feats) or concrete measures of partial achievement. In-kind support includes, for example, access to necessary equipment and laboratories.

4.3.2) Prize adaptation during runtime increases the chances of prize program success.

The ability to adapt during runtime refers to the ability to introduce changes in the architecture and governance of competitions as a result of new contextual conditions or developments in the very competition process. For example, a rule that governs a competition may require changes if it turns out to represent a barrier to innovation (which could occur if, for instance, entrants are asked to use certain materials or processes and they discover, over the course of the competition, that only alternative approaches can make final achievement feasible). The changes introduced in the Automotive X Prize's rules are a practical example. Murray et al. (2012) note that such changes involved the relaxation of vehicle feature requirements in several areas such as top speed and acceleration. This adaptation not only removed barriers to innovation but also contributed to maintaining many teams in the competition (Burstein & Murray, 2016).

Yet, changing rules can take a toll on the effectiveness of prizes. Kay (2012a), for example, interviewed Google Lunar X Prize entrants that expressed discontent – particularly those that had progressed the most in their projects – because of changes in rules after the competition has started. Moreover, prizes are a phenomenon that occurs in the context of broader economic, social and policy changes and external factors could significantly affect prize programs. After a synthesis of recent prize cases, Liotard &

[13] Still, prize sponsors have often incorporated provisions for technology licensing that require entrants to negotiate intellectual property rights in good faith.

Revest (2017) concluded that new regulations and policies, social actions, or even lobbying behaviors could affect a contest.

While some scholars recommend flexibility, there is evidence that suggests that prize rules, particularly those that govern the conditions of participation, prize duration, and submission of entries, should not look subjective or ever changing to contestants. Unfortunately, the literature does not offer insights into how to anticipate the need or prepare for change, so that sponsors can include provisions in the design stage or succeed in prize governance. Moreover, the case studies that highlight the potential negative effect of changing rules do not tell what the appropriate balance is between specific, concrete rules defined ex-ante and flexible rules that can change if necessary.

Ideas for sponsors

✓ Consider prize runtime changes if necessary to:

- Remove barriers to innovation, such as those resulting from feature requirements in expected solutions that could limit creativity of entrants.
- Level the playing field by removing requirements that involve the use of resources not readily available to all entrants.
- Adapt to contextual changes, by introducing, for example, new performance requirements in the event that non-participants meet the original requirements.
- Correct other changing conditions when, for example, the place where entrants must do their technology demonstration results inappropriate and a new place has to be chosen.

4.3.3) The cost of a prize program can significantly exceed the cash purse.

The total cost of prize programs is a topic that has received little attention from the empirical literature. The cash purse, or monetary rewards in general, is typically considered the only or the single most significant item in a prize budget.[14] Yet, anecdotal accounts and some evidence suggest that this is not the case in practice.

Prize program costs could easily duplicate the value of the monetary reward. A few examples from the empirical literature are illustrative. The total cost of the DARPA Challenges program for autonomous vehicle development was at least twice as much as the cash purse (which was, considering first, second and third place prizes, $6.5 million in three years) (Kay, 2011b; Nardi et al., 2016). In that case, the total expenditures included, in addition to the main prize, items such as seed grants to support teams, personnel appointed to the program, site visits to evaluate the work of entrants, and the organization of qualifying rounds. Also historical prizes often had total a cost that greatly exceeded the cash purse. Brunt et al. (2012), for example, found that, in 19th Century U.K. agricultural prizes, which substantial rewards of up to £500, sponsors had to carry trial tests that would cost up to £5,000 a year to choose the winners.

Since there are no evidence-based formulas or methods to plan (let alone estimate) costs and benefits of new prize programs, sponsors can learn more about managing

[14] This is even the case in the progress reports on the implementation of the federal prize authority resulting from the America COMPETES Act, where, for example, the first item on a list of benefits of prizes in the public sector is "establish an ambitious goal and pay only for success" (see OSTP, 2014, p. 8).

resources in prize programs from practical experience. Still, empirical evidence should address two key questions: How can sponsors maximize the outcome of prizes per dollar of budget? What conditions make prizes more cost-efficient compared to other incentives?[15]

Ideas for sponsors

✓ Review annual progress reports on the implementation of the U.S. federal prize authority to obtain reference values on the cost of government prizes and inform budget estimates.

✓ In the case of major prize programs, consider partnerships to share costs as authorized by the America COMPETES Reauthorization Act of 2010.

4.3.4) Strategic announcement can increase prize effectiveness.

The Internet and new communication means such as online social networks open up new possibilities for prizes. Moreover, their existence is possibly the single most important difference between the contexts of historical prizes and modern competitions. Today, sponsors can, for example, promote prizes around the globe to engage more and more diverse participants, or target specific communities of solvers through vertical social networks such as those created for professionals or artists. Yet, this social media-charged environment also calls for increasing efforts to position and differentiate prize initiatives in the media and compete for the attention of the public and potential entrants.

The little evidence on this matter still illustrates the importance of strategic prize launch. The announcement of the Google Lunar X Prize at the Wired NextFest 2007 event in Los Angeles, California helped the sponsor – The X Prize Foundation – attract certain types of solvers of particular interest for this kind of project – individuals and organizations that could be interested in the prize vision but not the typical corporate players in the space industry. However, this was ineffective to attract some international entrants who learned months later about the competition through the Internet (Kay, 2012a). This case shows how especially relevant this could be if sponsors seek to engage specific communities or reach certain audiences to raise awareness. Narrowly defined, specialized contests announced through mainstream media might not catch the attention of potential entrants. Conversely, more general-purpose competitions announced at niche venues could remain unknown to most of its target audience.

Government prize sponsors can post challenges to Challenge.gov but also make prize announcements through other means. Unfortunately, the literature does not offer more concrete insights into how timing and location parameters can be set for maximum effectiveness, or how they could vary across types of competitions. It neither addresses the potentially negative effects of announcing at venues that are not appropriate for the prize. No research has looked into the role that social media plays in prize announcement and how these means can be utilized to increase the effectiveness of prizes.

[15] Scholars do not discuss the counterfactual either (i.e. How much would have been the cost to obtain a solution through other means?). In this synthesis, only a general reference by Gustetic et al. (2015) states that, in some Centennial Challenges prizes in which entrants contributed useful innovations, NASA saved "taxpayer dollars by not contracting out a lengthy research program to seek an answer".

Ideas for sponsors

✓ Watch for community or industry events that represent opportunities for additional media exposure and announce competitions at venues likely attended by the desired target audience.

✓ Watch for public events that could overshadow the prize announcement if they coincide on time or location.

4.3.5) Active participation and the formation of communities can sustain the effect of prizes over time.

Some evidence suggests that active participation of entrants and the formation of communities of solvers can sustain the effect of prizes over time. Kay (2012a), for example, observed that both an annual conference held for participants of the Google Lunar X Prize and the competition's web blog kept participant teams engaged and promoted the formation of professional networks. Kay (2011a, 2011b) also noted interactions and collaboration between Northrop Grumman Lunar Lander Challenge's participants and the formation of a community of "makers" who work on robotics as an outcome of the DARPA Challenges. This relationship is also discussed in the more general (i.e. empirical and non-empirical) prize literature. In particular, terms related to "prize sustained effects" are associated with topics such as perceived active engagement of participants and community formation (Adamczyk et al., 2012).

Still, it is not clear how this relationship plays out in practice, that is, whether community formation is a prize outcome or something sponsors should promote. It is also unclear how this relates to the more general topic of co-existing collaboration and competition in prizes (see section **Governance 4.3.6**). Adamczyk et al. (2012) identified the topic "activation" in the literature – an aspect of prize design that sponsors could work on – but do not provide details into the use of community formation as a means to increase engagement and the effectiveness of competitions. Other scholars imply that the formation of communities is inherent to prizes, despite their competitive nature. More generally, the forms of engagement that are ideal in each type of prize and possible variations in how actively contestants participate in competitions remain unclear.

Ideas for sponsors

✓ Due to a lack of more robust evidence, sponsors should review more general literature to examine prize case studies in both private sector and government to source ideas on effective means adopted to engage participants (such as conferences, workshops, and online forums).

4.3.6) Knowledge sharing between teams can be induced to have more intense, effective competitions.

Knowledge sharing and spillovers are common in prizes but scholars study the phenomenon from different viewpoints (see, for example, Davis & Davis, 2004; Brunt et al., 2012; Kay, 2011a). A more general perspective notes that they are a result of informal

cooperation between entrants and the formation of communities of solvers (see section **Governance 4.3.5**), or occur because entrants can generally observe the work and achievements of other entrants in industry exhibitions and technology demonstration days that are part of the prize.

An alternative perspective focuses on the positive effect of knowledge sharing on the intensity of competitions. Nardi et al. (2016), in particular, based on their study of robotics prize cases, argue that gently enforced openness (through, for example, shared solutions and tools, the development of community infrastructure and resources, and the relaxation of entry requirements) makes competitions more competitive, fosters interactivity between teams, and encourages diversity of participants by minimizing the barriers to entry.

While there is wide agreement on the presence of these phenomena, there is little empirical knowledge on how to effectively induce openness and knowledge sharing and, more importantly, how prevalent these phenomenona are and whether they are cause or consequence of sponsor actions. This aspect of prizes is linked to potential privacy and confidentiality issues, particularly if prize sponsors are government entities. Entrants may be willing to share information on their projects or even cooperate with other entrants but might be reluctant to share certain information if there is some form of enforcement or reporting requirements by government agencies. The latter might make a prize less attractive and lower participation.

Ideas for sponsors

✓ Unless more concrete evidence is made available, adopt a more passive approach to knowledge sharing and information requirements.

✓ Use public events such as prize exhibitions or "demo days" as means to disseminate knowledge and promote cooperation in the process of finding solutions.

✓ In long-term prizes, host regular prize conferences where teams can share ideas and network with other participants.

4.4) What is the outcome of prizes?

4.4.1) Prizes can induce and accelerate innovations over and above what would have occurred anyway.

The empirical evidence suggests that prizes can induce and accelerate innovations over and above what would have occurred anyway, but it is still not as conclusive as some advocates' claims are. Diverse prize outputs illustrate such an innovation effect. Data on the R&D activities of entrants in aerospace prizes, for example, show that entrants introduced novel designs and new-to-aerospace-industry, software-like development process (Kay, 2011a). An investigation into the effect of NASA's Centennial Challenges prizes also found evidence of both new activity – projects started "from scratch" – and ongoing technology development that prizes accelerate, being the latter activity undertaken by "platformers" or teams that had been developing their technology before prize announcement and enter competitions to field test and validate it (Vrolijk & Szajnfarber, 2016). Yet, these novelty and increasing activity cannot be completely

isolated and entirely attributed to prizes since they relate to both new and existing projects (see sections **Opportunity 4.1.2**, **Opportunity 4.1.4**, **Design 4.2.1**).

Interestingly, while a number of historical prizes have been the success story typically presented by prize advocates, the evidence on their effects is contradictory or inconclusive at times. A synthesis on early 20th Century aviation prizes, including the popular Orteig Prize, offered in 1919 for the first non-stop flight from New York to Paris, for instance, concluded that prizes "jumpstarted" the aviation industry (Macauley, 2005). Other scholars, however, found that the value of inventions in some historical prizes may had not been as significant as shown by some overlooked measures. Khan (2015) explains, for instance – albeit without explaining how pervasive this case was – that winning entries in some prizes had been already invented before prize announcement. In Masters' (2006) words, "often, much of the work was done for other reasons, even before the prize was offered".

Moreover, no research has yet determined precisely how prize design features induce each type of innovation (see section **Design 4.2.3**). The evidence available in this regards might not be generalizable. Kay (2012a), for instance, argues that the Google Lunar X Prize has led to the development of a range of technologies (some of them commercialization-ready) and the introduction of new-to-industry business models. The latter – he argues – is the result of significant costs associated with the prize projects and entrants' lack of upfront funding to conduct their activities. Prizes in other sectors or that set different conditions could lead to different results. Another important aspect that remains unclear is how alternative prize designs or prizes offered at different points along the process of technology development relate to ongoing and new R&D processes. For example, prizes could offer the additional incentive needed to complete ongoing projects or the motivation for scientists to start investigating an issue of interest.

Ideas for sponsors

✓ Consider prizes part of broader technological processes and a phenomenon connected to ongoing R&D projects and technological trends.

✓ Identify ongoing projects and relevant technological trends to be able to tease the effect of prizes out of more general innovation processes.

✓ Accelerate projects of interest for the agency by aligning the prize challenge with the technology those projects focus on.

4.4.2) Prizes benefit both sponsors and entrants regardless of the final result of competitions.

The evidence shows that prizes benefit both sponsors and entrants regardless of whether the prize problem is eventually solved. Typical aims of sponsors – such as public education, raising awareness about issues of interest, comparison of technological approaches to solve a problem, technology showcasing, or gaining understanding about the nature of a problem – are often realized well before the prize is awarded. Similarly, entrants often find satisfaction to their diverse motivations (see section **Design 4.2.2**) – such as publicity, attention, popularity, credibility, or access funds and testing facilities –

as soon as they join a competition, without necessarily being a runner up or eventually claiming the reward.[16]

The literature offers several examples of these immediate benefits of prizes. Davis & Davis (2004), for example, note how prizes (such as aviation and the Super Efficient Refrigerator Program prizes) have helped sponsors promote their ideas and activities of interest and publicized the technologies developed by participants. A study of the DARPA Challenges and recent aerospace prizes by Kay (2011b) points out that prize managers gained key insights into the means to solve technical problems and the state of the art and technological possibilities in both autonomous vehicles and aerospace by comparing the approaches adopted by participants over the course of competitions. Nardi et al. (2016) also conclude that robotics prizes help students and teachers develop several types of technical skills including interdisciplinary teamwork. Gustetic et al. (2015) conclude that NASA's Centennial Challenges prizes enlarge the sponsor's understanding of the solution space for a particular problem area. Murray et al. (2012) and Kay (2012a) also list those diverse benefits that entrants obtain from prize participation and, furthermore, Kay (2012a) suggests that the main goal of certain entrants could be to obtain these short-term benefits and not necessarily win the competition.[17]

The implications of this finding are very important and call for a conceptual distinction between *benefits* and *objectives* in the context of prizes. While the benefits – more generally, the positive outcomes – of prizes can be immediate (and even unexpected), the objective(s) of a prize program represents the ultimate goal the sponsor aims for. It relates to the sponsor's mission and must be defined ex-ante, in measurable terms, so that a proper evaluation of the prize program is conducted after its completion. The benefits emerging from prizes may or may not relate to or be a measure of accomplishment of such an objective (see section **Discussion**).

The literature generally fails to make a clear distinction between benefits and objectives and, therefore, does not explain how sponsors can design prizes with concrete, achievable and measurable objectives that also maximize the benefits obtained by both sponsors and entrants. For instance, the literature emphasizes the educational contribution that prizes can make (e.g. Adamczyk et al., 2012; Nardi et al., 2016) but does not offer insights into whether this is valid for all levels of education and performance or what a concrete measure of such an effect is, in terms of, for example, improved skills. Similarly, the literature coincides on the ability of prizes to showcase technologies and enable learning by comparison (e.g. Davis & Davis, 2004; Kay, 2011b, 2012a; Gustetic et al., 2015) but does not offer concrete indication of how and when that ability exists in practice or translates into specific inputs for the prize design process so that it is considered as a program objective.

Finding a winner and awarding the prize is still an important part of the prize process. Prize awards are not only the culmination of a successful competition but also a means for the sponsor to maintain its credibility and authority in the field (Leverence, 1997). Moreover, completion of this process is also necessary to fully realize some of the

[16] This is generally speaking. There are prizes that require certain measure of performance to qualify for certain benefits such as, for example, seed money support for prize projects.

[17] The argument is that, while every prize entrant would like to win the competition, some entrants are perfectly aware of their limitations and low chances of winning. This, however, does not stop them from seeking to enter competitions to be able to access short-term benefits.

benefits of prizes. For instance, monitoring the work of entrants could provide valuable insights to compare technological approaches, but knowing what the best performing technology ultimately is can inform better decisions on eventual technology adoption.

Ideas for sponsors

✓ Adopt an objective-driven approach to prize design using measurable and concrete indicators of achievement that can later help evaluating the prize and assessing its contribution to the agency's mission.

✓ Identify the potential benefits that could result from a prize and the best way to tap into these to increase the value that each prize program adds to participants and the agency's mission.

✓ Map potential benefits and types of entrants and develop insights into how to attract certain communities of interest by targeting specific motivations.

4.4.3) Prizes have a signaling effect on resource allocation.

Prizes have a signaling effect that stems from either the prize value or the value of related technologies. Based on a synthesis of diverse prize cases, for example, Masters (2008) and Masters & Delbecq (2008) conclude that a relatively small amount of prize money can already send a strong signal and attract attention and investment in prizes. Brunt et al. (2012) concluded that this signaling mechanism also existed in historical prizes that offered medals (and not a cash purse) as a reward. Furthermore, the empirical evidence also suggests that prizes could signal potentially profitable areas of technological development and attract investments to them. In recent aerospace prizes, for example, there are instances of projects that had been stalled and/or abandoned and later on reactivated upon the announcement of the Google Lunar X Prize (Kay, 2012a; Vrolijk & Szajnfarber, 2016).

After all this is, rather than a new finding, a more concrete explanation of the underlying mechanism through which prizes induce innovation. As such, it helps explain the decisions to enter competitions and the overall effect of prizes on R&D and innovation. Interestingly, this signaling effect may sometimes be negative. For instance, when there are competition timetables for a series of prizes with pre-defined technology foci (e.g. annual robotics competitions) prizes could send more complex signals with ultimate negative effect. Brunt et al. (2012) note that, in that case, entrants speculate about the best moment to enter competitions and cause irregular prize registrations. Davis & Davis (2004) also raise a word of caution because prize signaling effects could divert funding from other potentially more socially desirable projects.

In any case, there is no concrete evidence on how significant this signaling effect is or how it varies across types of prizes and technologies, and what factors (in addition to the cash purse, e.g. sponsor's promotional efforts) determine whether such a signaling occurs. Moreover, the literature is somewhat vague when describing the effect and its causes (e.g. "a well-designed prize", "a small amount of prize money"). Finally, while some literature identified specific instances of resource re-allocation, it failed to delve into this phenomenon to learn whether it can also be the result of other non-prize factors.

Ideas for sponsors

✓ Consider prizes as an expression of interest in particular technology areas.

✓ Avoid reference to any particular type of solution in prize challenge definitions to avoid discouraging investment in other potentially desirable R&D areas.

✓ Use prizes to incentivize the reactivation or acceleration of lines of research and technology development that are stalled and are deemed of interest.

4.4.4) Prizes can induce novel R&D and industry practices.

Scholars have considered the potential of prizes to attract fresh ideas and approaches to problem solving, but this effect of prizes is generally overlooked and, to date, has accumulated little empirical evidence. The latter include some insights from aerospace competitions such as the Google Lunar X Prize and NASA's Northrop Lunar Lander Challenge, where participant teams introduced iterative development and commercialization-oriented business plans and activities not typically seen in the aerospace sector. This effect has been linked to the participation of "unconventional entrants" and a lack of upfront funding in the context of complex, costly projects (Kay, 2012a).

The attention paid to winning entries generally overshadows this potentially valuable prize output. Understanding the approaches that prize participants adopt in their projects could help not only make prizes more effective overall but also shed light on the actual capabilities of the participants and the kind of resources they need to accomplish prize challenges. This is particularly relevant if the objective of a prize is, for example, the development of new methods and standards, or if prizes involve significant R&D efforts.

Whether this novelty exists in every prize or in sectors other than aerospace is unclear. Moreover, the definition of "unconventional entrants", while frequently used in both empirical and more general literature, is still fuzzy and does not entirely explain the kind of contributions these entrants can make.

Ideas for sponsors

✓ Consider means to learn about novel approaches to technological development introduced in competitions during runtime (by the time a prize is won, the focus is likely to be on the winning entry).

✓ Prize conferences may promote knowledge exchanges, particularly between entrants and agency officials. These conferences could focus on new practices and methods that could be used to tackle problems. Online forums could also accomplish a similar goal.

4.4.5) Prize outputs may include technologies that are not adoption-ready.

Prizes can induce R&D activity in a wide range of technologies but these may not be always ready for adoption or use by sponsors. The kind of participants that could enter prizes and the more general dynamics of this instrument explain this. Scholars have identified, for example, "unconventional entrants" (participants that do not have experience with the prize technologies) that contribute novel technologies in both privately held and government prizes (Kay, 2011a, 2012a) and new-to-technology

entrants that started "from scratch" in NASA's Centennial Challenges (Vrolijk & Szajnfarber, 2016). These entrants may introduce fresh ideas and novel approaches to problem solving, but the technology they build is often not readily available for adoption or commercialization.

More generally, a major part of the prize technologies can actually be at low technology readiness levels, that is, at a proof-of-concept, design or experimental level (Kay, 2011a, 2012a). Moreover, these technologies are sometimes insufficiently documented to comply with standards or enable seamless adoption. While inexperienced or poorly funded projects could be a reason for this, a lack of additional incentives to further develop the technology is also a plausible explanation. The latter could be the case of prizes improperly targeted such as those offered too early along the process of technology development (cf. Davis & Davis, 2004). The empirical literature does not fully explain how prize design parameters relate to the "readiness level" of outputs.

Ideas for sponsors

✓ Design more narrowly focused prizes if their purpose is to promote technology development for procurement. In this case, specify potential contract conditions that include documentation and standards that could facilitate adoption.

✓ Offer additional or more specific incentives to encourage entrants to work on project and solution documentation using, for example, industry standards or the agency's guidelines for technology procurement.

4.4.6) Prizes induce knowledge diffusion.

Knowledge sharing and diffusion are among the often-cited benefits of prizes yet, in some cases, may also be a factor that determine prize success. Indeed, as discussed in section **Governance 4.3.6**, knowledge sharing and diffusion may need to be promoted in order to make prize competitions more exciting and competitive or support goals such as community development, education and training.

Scholars argue that the ability of participants to observe the design and performance of each other's entries is among the main causes of significant spillover effects in competitions. That occurs at exhibitions and "demo days", when participants are asked to present their inventions or accomplish certain feat to demonstrate their technology's performance in order to qualify for or be able to claim the prize (Brunt et al., 2012; Kay, 2011b, 2012a). According to Davis & Davis (2004) this openness inherent to the prize process led some inventors to take development paths other than prize participation in early 20th Century aviation prizes.

Yet, theoretically, compared to patents, which have a built-in disclosure mandate, prizes do not necessarily promote the diffusion of knowledge. Hence, entrants can decide to maintain secrecy. This result has been observed in at least one historical prize case study (the XVIII Century Longitude Prize) and considered a barrier to incremental innovation (Burton & Nicholas, 2017).

The empirical literature does not offer a concrete measure of the extent of the knowledge diffusion phenomenon, or insights into how it varies across types of prizes and technologies. For example, the link established between diffusion and public technology demonstrations or performances raises the question of whether knowledge

diffusion can occur in prizes where direct observation of entries is difficult or impossible (e.g. prizes that require laboratory work or proof). Moreover, much of the literature addressing this issue has focused on historical prizes. Contrary to modern competitions, prizes announced decades or centuries ago did not have access to communication means such as the Internet nor the incentives to share that social media create. While more recent competitions have tapped into these new tools, scholars have not investigated their use and value added to competitions.

Ideas for sponsors

✓ Use public technology demonstration events or "demo days" to both foster knowledge exchange and dissemination and further attract the media and general public.

✓ Use private events such as prize conferences to further promote interactions between participants while producing feedback on the development of competitions to anticipate governance issues.

✓ Tap into social media applications to enable "real time" knowledge diffusion in prizes.

4.4.7) The ability to adopt prize technologies depends on the sponsor's organizational characteristics.

Sponsors may want to adopt the technologies developed in the context of competitions. While evidence suggests that whether this is possible depends in part on the quality of the output of competitions (see section **Outcome 4.4.5**), some scholars argue that this ability also depends on the organizational characteristics of the sponsor. Mergel & Desouza (2013), in a study of the Challenge.gov program, identified rigid internal processes that made difficult to incorporate most prize solutions into agencies' administrative processes and service offerings. However, they note that public sector innovation in the form of new or changed public services is generally introduced as a result of the policy cycle. Therefore, while agencies have been directed to incorporate new technologies using instruments such as prizes, organizational rigidities limit their ability to appropriate the value created through competitions. Such a study does not describe the prize design factors (if any) that could facilitate the adoption of results.

Ideas for sponsors

✓ Consider the introduction of technology adoption aspects in the process of prize design.

✓ Consider aspects such as intellectual property licensing, documentation of outcomes, use of standards, timelines for technology adoption, and, if necessary, mechanisms to further develop prize entries to match the agency's requirements for technology adoption.

4.5) How should sponsors evaluate prizes?

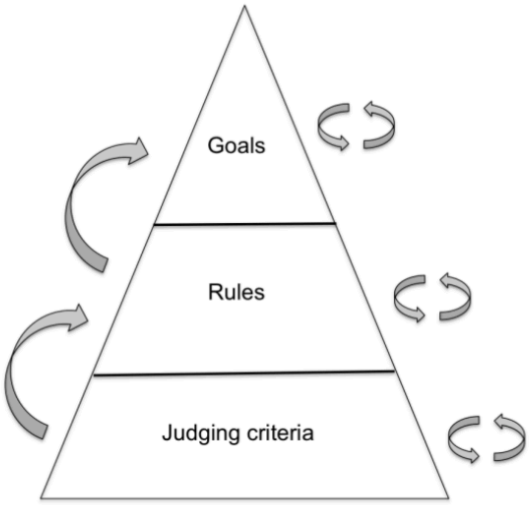
Prize evaluation is by far the topic that received the least attention in the empirical literature. A prevailing approach to prize design and implementation that is not

necessarily objective-driven is likely to be among the main reasons for this. From the academic research viewpoint, a lack of more solid constructs and work on prize model development make evaluation research difficult to accomplish.

We identify three sources of insights into prize evaluation in the literature, but little evidence and actionable recommendations. Those sources include models of prizes that adopt a specific perspective, more general models that address the prize process as a phenomenon that occurs in a certain context, and guidelines elaborated based on direct or indirect prize experience and other literature.

Burstein & Murray (2016), for instance, develop a model grounded on theory of institutions and administrative law (Figure 1) and probe such a model with the Progressive Insurance Automotive X Prize case study. It focuses on prize governance in the context of government institutions. Concepts such as experimentalism, learning, collaboration and flexibility in problem solving characterize this model. It reflects the typical uncertainty of prizes – the prize sponsor appears as a coordinating entity that initiates the process and responds as new information is gathered. Trust building over collaborative iterations motivates entrants and legitimates the prize process.

Figure 1. Model of governance structure in innovation prizes



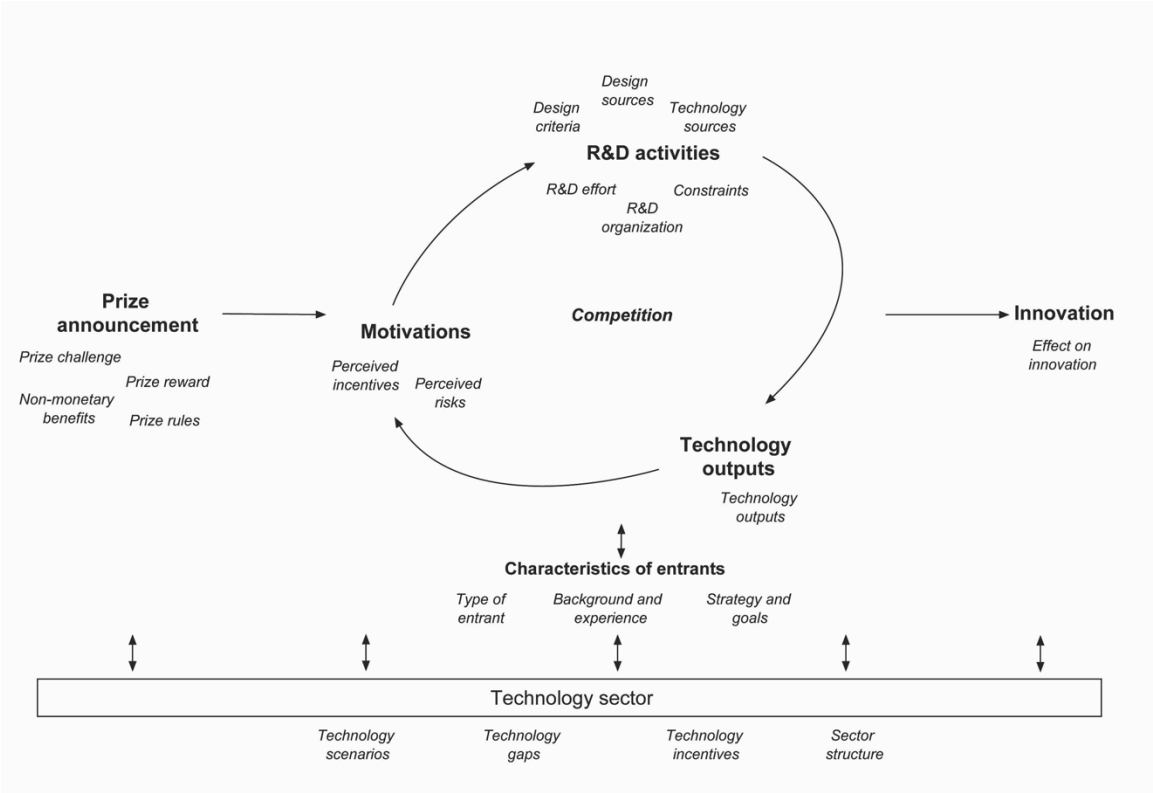
Source: Burstein & Murray (2016).

This model highlights three main constructs and elements of prize governance, namely judging criteria, prize rules, and goals. These are all elements defined ex-ante yet, as the authors explain, competitions should remain open and flexible to necessary changes as competitions unfold. These three elements also represent aspects of evaluation in a prize program that sponsors should consider. Moreover, the dynamism that the model contemplates suggests that evaluation must be conducted not only ex-post when the outcomes are apparent, but also *during* competitions to feed back into the prize process.

Kay (2011a, 2012a) introduces a more general, theory-grounded and empirically probed logic model, aimed at both prize design and process evaluation (Figure 2). This model features a multi-dimensional prize process and considers the prize in its economic and broader context, the prize competition as a discrete instance of an innovation process, and the dynamics of prize participants. In a structural approach, it seeks to tease out all

the key relationships between different levels of the phenomenon and the effect of prizes on innovation. Its empirical development and probe includes case studies in both private and public sector (the Ansari X Prize, NASA's Northrop Grumman Lunar Lander Challenge, and the Google Lunar X Prize).

Figure 2. Logic model of innovation prizes



Source: Kay (2012a).

This model comprises several elements of the prize process that sponsors can measure to evaluate the effect of prize programs. Unfortunately, the degree of complexity of the model and a lack of insights into what elements could be more important in each type of competition and technology sector leave up to the sponsor the decision on what factors should be measured more systematically. Still, the model describes more precisely the relationships between constructs that can help tease out the prize effects from the effects of other phenomena. Moreover, the timeline implicit in the model suggests points of data collection and possible runtime evaluation that sponsors could adopt.

A third source of insights into prize evaluation could be non-empirical literature or accounts that synthesize diverse other sources. Practical, actionable evaluation recommendations range from basic guidelines and indicators (see, for example, Kay, 2012a) to more elaborate guides that are part of the Challenge.gov Kit for prize sponsors (see, for example, Conrad et al., 2017). The value of these insights varies. Lists of prize output metrics, for example, are not a proper framework to evaluate prize programs but could give sponsors a general idea on the types of measurable outcomes, the points along the prize process where measures can be taken, and the aspects of design that can be compared among prize programs in a prize portfolio program. On the other hand, more

sophisticated approaches to prize evaluation could shed light on methodological approaches to prize evaluation to include, for example, economic modeling with specific application to prize problems to determine impacts and rewards or comparative assessments that take industry and technological standards into account to measure the performance of prize entries.

Ideas for sponsors

✓ Incorporate prize evaluation aspects in early phases of prize design. Define the main objective of the prize program and more specific, operational milestones.

✓ Consider key aspects such as the judging criteria to select a winner in the process of crafting rules and defining goals and also incorporate these elements in the final evaluation of the program.

✓ Consider evaluation (and corresponding data gathering) opportunities at different points of the prize process and not only in a post-prize phase. Runtime evaluation could provide valuable feedback to manage and adapt competitions to their context.

✓ Borrow concepts from other sectors such as Test Driven Development in software processes, to design prize actions based on concrete tests and experimentation to improve results.

5. Discussion

The potential of properly designed prizes to induce positive effects and help sponsors accomplish diverse goals is undeniable, but key questions remain unanswered. The empirical evidence on these effects is still limited, some times vague and other times contradictory. While experienced prize sponsors and managers use prize competitions and learn "by doing", newcomers should consider the use of prizes carefully. They still are experimental tools. The lack of more concrete insights to support objective-driven design of prizes is the most significant knowledge gap that sponsors will encounter.

Deciding on appropriate opportunities for using prizes and the successful implementation of prize programs require significant prize and industry expert input. Knowledge on the state of the art of the technology, the potential solutions space, and existing communities and industry incumbents is necessary. There is a general agreement on the need for open and flexible prize designs to enable creativity and effective governance and tap into outsiders for fresh ideas. "Open" and "flexible" are fuzzy concepts but emphasize how dynamic prizes can be, how much they depend on their broader context, and how much uncertainty the prize process has. Sponsors might need to design prize features in contingent or relative terms in anticipation for necessary changes and unexpected developments in competitions and their context. Prizes might ultimately not work as intended.

Prizes can induce new R&D activity but also draw on existing technology, industry projects and ongoing activities of those who later become prize entrants. The most active, exciting, successful prizes could be those that tap into knowledge from mixed sources, take advantage of existing technologies, and enable diverse participation and approaches to solve the problem. Attracting participants and establishing new communities of solvers might require unorthodox approaches, practices that are new to government agencies.

Combinations of monetary and non-monetary rewards (and not just a single big cash purse) should be considered. Communication means such as social networks and the endorsement from "influencers" or public figures can play a strategic role to promote prizes and attract resources to them. There may be other more subtle mechanisms to make competitions more exciting such as promoting knowledge sharing among participants, though knowledge diffusion could actually be an intrinsic feature of certain prizes. This kind of ambiguity – whether a given aspect of the prize phenomenon is an emerging feature or a design parameter – is, unfortunately, frequent in the empirical literature.

The factors that determine the ability of prizes to induce incremental innovation or breakthroughs have not yet been clearly identified. Exogenous factors such as the state of the art of the technology or ongoing industry processes could be important determinants in this regard, even more relevant than the design parameters sponsors can directly set. Moreover, prize outputs may still not be adoption-ready by the time a competition ends and require further development for their inclusion in the sponsor's projects and organization. Sponsors should not overlook potentially valuable intermediate outputs of prizes, such as new methods and practices that entrants introduce while working on their solutions to the prize problem.

Existing incentives, including sizable markets and intellectual property protection, may affect the decisions to enter and invest in prizes, and ultimately, increase or moderate the effectiveness of prize programs. Prizes may signal potential opportunities in certain areas, but those signals become part of a more complex context with diverse other opportunities for technology development and commercial exploitation of innovations. This may cause the effect of prizes to fade away in the longer term, but the evidence is not conclusive in this regard.

Prize programs can generate valuable data to inform future prize design and evaluation. New-to-prize agencies may need to go through a phase of experimental designs first to determine what is best in each case. Both prize data and properly defined objectives play the important role of enabling program evaluation. Teasing out prize effects from non-prize phenomena is the crucial (and challenging) mission of the prize evaluator. Assessing the general benefits or positive externalities resulting from the use of prizes, which may or may not be a consequence of purposeful design, is also key.

Overall, prizes are resource-intensive and could become a costly approach to innovation. Generally, only winning entries receive awards, yet successful prizes may need to provide additional support to participants and adopt costly governance processes. In addition, entrants will likely tap into widely distributed technological, financial, and social resources to fund their efforts. This ability of prizes to leverage resources is appealing but might also influence R&D and investment decisions in unexpected ways. They could, for example, signal a preference for certain technological approaches over alternative solutions that could be more efficient or sustainable. Moreover, because of the extent to this phenomenon, it might be difficult for sponsors to obtain a concrete measure of the external resources competitions tap into and, hence, a sense of how efficient the prize program is.

Prizes are complementary to other incentives for innovation and do not necessarily represent an alternative tool. Contextual factors such as economic conditions, the dynamics of industrial sectors, policies and even social events can play a role in both the

decision to use prizes and their final outcome. We know little about how much the context can influence prizes, but we do know that this influence varies over time as competitions unfold and from one prize to the next. On the other hand, legal and regulatory frameworks also influence prize design and governance. They can constrain the scope of application of prizes, prolong their design phases, and also determine whether prize results can effortlessly be adopted by agencies.

A number of aspects of the prize phenomenon have not yet been empirically investigated. Findings focus on more general issues and often fail to provide concrete examples of phenomena that occur in the context of competitions. The usual focus on prize cases deemed successful and the positive benefits they led to reinforces the prevailing assumption that "prizes work". Scholars have not generally made a distinction between prize benefits and program objectives (see **Outcomes 4.4.2**). In our dataset, only Gustetic et al. (2015) and Khan (2015) (with regards to historical prizes) discuss more specifically aspects of inappropriate design and the negative consequences of ill-designed prizes. This kind of knowledge is probably shared informally among prize experts, but the academic literature has not investigated prizes from this perspective. Moreover, we note that some times the literature makes claims that are not fully supported by empirical evidence and faces potential biases when it is based on historical accounts and/or media coverage (and not first-hand data). Some conflicting and inconclusive evidence also exists in the case of historical prizes, which is likely the result of a lack of more robust prize datasets or simply missing data.

The lack of empirical research and evidence is notable in at least two important, broadly defined research thrusts. The first thrust relates to theory building and the models and basic constructs that researchers develop to conduct empirical research. We find only a handful of empirical works that made significant contributions to model government prizes (e.g., the governance model work by Burstein & Murray, 2016; the logic model of the prize process by Kay, 2011a). Models are valuable for both research and practice. They can help organize the many constructs that emerge from the literature in terms of causation or correlation relationships and guide empirical research that is both internally and externally reliable. They can also help practitioners understand, for example, what prizes can and cannot do for them and whether some elements of the prize process are design parameters or phenomena inherent to all prizes. The latter is essential to pursue objective-driven prize design.

Moreover, the development of standard categories (or "types") of prizes would be very valuable for both practice and further research as well. They could enable comparisons and make systematic the process of collecting evidence to draw lessons and make recommendations. Similarly, the development of taxonomies of prize entrants based on one or more of their attributes would be very valuable to investigate their motivations and response to incentives and design more effective prizes. This is very important from the practical standpoint as sponsors generally target certain communities of interest or types of solvers.

The second research thrust is more topical and relates to pending questions about the use of government prizes. We identified 16 select topics that have received little attention from empirical research in our five synthesis themes (see **Appendix I**). While prize evaluation is the theme that has received the least attention, key topics in other themes also call for further investigation. The introduction of evidence-based models that reflect

how prizes actually work in practice and the development of test cases or credible estimates on how innovation would have evolved in a counterfactual world are among the prize evaluation aspects that need the most research on (Kay, 2012b; Williams, 2012).

The reason prizes have become so popular and widely adopted while there is so little empirical evidence on their effects is another interesting question. This synthesis has not attempted to answer this question but we do note that there are somewhat uniform phases of the use of modern government prizes and a progression in empirical research. Private initiatives and, from the literature standpoint, anecdotal accounts of historical prize cases define a first "Renaissance" phase that roughly spans the years from 1990 through 2005. This phase coincides with the emergence of the Internet, which was successfully exploited by prizes such as the Ansari X Prize to capture the attention of large audiences. Except for a handful of scholarly works, this phase did not see much prize research. Nevertheless, it did represent an increase in media attention and commentary and sparked discussion in policy circles.

A second "Exploration" phase that spans the years from 2006 through 2015 coincides with the beginning of empirical research and the initial use and expansion of government prizes. This appears as a phase of experimentation and learning about the possibilities of this incentive, but academic research still lagged behind. It was largely descriptive and focused on the diverse benefits and positive externalities of prizes. The third and recently started "Understanding" phase appears to mark the beginning of a new period of more knowledge intensive prize design, possibly informed by more robust, systematic empirical research.

Assumptions and oversimplifications such as "prizes work" and "sponsors pay only for results" prevailed throughout most of these phases and made prizes interesting and exciting. As a result of their immediate effect, prizes attracted public and media attention, particularly when they offered sizable rewards. Agencies that pioneered the use of prizes positioned as "innovators among innovators" and made a name for themselves. This was in part possible because, regardless of the result of competitions and the value of their technologies, prize announcements spark diverse activity and raise awareness. Whether prize programs accomplished concrete objectives is a separate question.

We note that, to date, the literature reports on prizes generally designed to contribute to broader aims, such as "to be beneficial to the world" or "to educate the public", that is, they are defined in terms of more general and aspirational goals, not concrete, measurable objectives. This could reflect the underlying tension between the nature of this instrument and the need for accountability in government programs. On the one hand, aspirational goals likely help in the process of communicating the prize idea and engaging participants, the media and the public. Yet, on the other hand, measurable objectives are necessary to evaluate the outcome of public programs. Solving this tension is among the challenges the practitioner faces and the key questions for the academic researcher.[18]

Theoretical models and the non-academic literature often understate the complexity of the prize phenomenon. And, if prize sponsors do not design prizes to meet specific

[18] Some references in the literature suggest that this could actually be a significant challenge. For instance, research on prizes conducted by NASA – one of the pioneers in the use of government prizes – points out that the agency has moved toward an objective-driven approach to competitions after 10 years of prize program experience (cf. Gustetic et al., 2015). The synthesis literature shows no data on other agencies adopting a similar approach or prize cases with specific, quantifiable, pre-defined objectives.

objectives, they might fail to account for failures or uncover the true potential of this tool, let alone learn about the internal or external causes of their failures and successes. Objective-driven prize designs are more knowledge intensive. They require systematic knowledge on how different design parameters affect (negatively or positively) outcomes and contribute to advance the sponsor's mission in a concrete manner.

6. Concluding remarks

This report synthesized empirical knowledge to clarify what is known and what is not known about prizes with regards to their use in science and technology policy. It focused on innovation prizes or *grand challenges*, which have attracted much attention and influenced the design of the Challenge.gov platform. Notable examples of prizes of this kind include the DARPA Challenges for autonomous driving vehicles and NASA's Centennial Challenges to develop a whole range of space technologies. These programs have shown the potential of prizes as a policy tool, but scholars and prize advocates have discussed ideas for prizes to achieve even more diverse and ambitious goals.

Policy makers should know that prizes are not only another kind of incentive for innovation but also a complex phenomenon. Moreover, prize design is knowledge intensive. Prizes can become a strategic tool in the portfolio of government agencies but, considering the existing empirical evidence, prize programs should remain exploratory and experimental. Prize programs are costly and require a clear definition of objectives, a strong data collection and evaluation component, and an incremental approach that can expand their potential as new evidence is gathered and prizes are evaluated. The consideration of complementary incentive mechanisms is important as well.

Further research should focus on two main research thrusts. The first comprises theory building work to further develop prize models and constructs. The second is more topical and addresses a number of key questions that remain unanswered, particularly with regards to prize evaluation. Researchers should take advantage of the large number of government competitions to collect more and more systematic primary data. Significant hands-on experience is also valuable – it can inform prize programs and also offer insights for further research.

A lack of a stronger body of empirical evidence makes several aspects of the prize phenomenon a black box. One of the most interesting questions is why empirical academic research still lags behind the increasing use of prizes in government. We believe that the answer is rather simple: "prizes work", that is, always generate some form of positive benefit despite of their cost and risk. Yet, objective-driven prize design, which is likely required for a more widespread use of prizes, is more knowledge intensive and difficult to achieve. It requires careful planning and execution and expert input.

We find valuable evidence on the potential of prizes but there are still important knowledge gaps that empirical research must close. Government agencies should use prizes cautiously and adopt more significant steps toward evaluating prizes before the implementation of large-scale prize programs.

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Appendix A: Timeline of prizes and their use in government

Time period	Select prizes / Policy milestones	References
XVIII Century	Longitude Prize is announced (1714).	Sobel (1996); Burton & Nicholas (2017)
XVIII Century	Royal Society medals are offered to promote science.	Crosland (1979); Bektas & Crosland (1992)
XVIII Century	Royal Agricultural Society of England awards given for agricultural equipment.	Brunt et al. (2012)
1907-1925	Early aviation prizes are held.	Davis & Davis (2004); Macauley (2005)
1919	$25,000 Orteig Prize is announced (won in 1927).	
1959	Kremer Prizes are announced (won in 1977, 1979, 1984)	
1994	$1 million Rockefeller's Prize for STD Test is announced.	
1996	The X Prize Foundation announces the $10 million Ansari X Prize.	
1999	"Concerning Federally Sponsored Inducement Prizes in Engineering and Science" report is published.	NAE (1999)
2004	"A Journey to Inspire, Innovate, and Discover", Aldridge Commission report is published.	Aldridge et al (2004)
2004-2009	DARPA implements DARPA Challenges program.	Kay (2011b)
2005-today	NASA implements its Centennial Challenges program.	Roman et al. (2017)
Jan. 2005	Introduction of H.R. 417 - Medical Innovation Prize Fund Act.	House Bill 417 (2005)
Nov. 2005	FY 2006 Science, State, Justice, Commerce and Related Agencies Appropriations Act (Public Law 109-108)	Science, State, Justice, Commerce, and Related Agencies Appropriations Act (2006)
2006-09	NASA holds the Northrop Grumman Lunar Lander Challenge.	Kay (2011a, 2011b, 2012a)
2007	Report "Prizes at the National Science Foundation" is published.	NRC (2007)
2007	X Prize Foundation announces the Google Lunar X Prize.	Kay (2012)
2009	The Obama Administration announces "A Strategy for American Innovation".	
Mar. 2010	OMB circulates the memorandum "Guidance on the Use of Challenges and Prizes to Promote Open Government".	Zients (2010)
Sep. 2010	The federal government launches Challenge.gov.	
Jan. 2011	American COMPETES Reauthorization Act gets enacted and authorizes all agencies to conduct prizes.	Furman (2013)
2011?	Bershteyn & VanRoekel's Memorandum for General Counsels and CIOs is published.	
Feb. 2015	Introduction of H.R.1162 - Science Prize Competitions Act.	House Bill 1162 (2015)
May 2015	Introduction of H.R. 6 - 21st Century Cures Act in House of Representatives (passed House).	House Bill 6 (2015)
Jun. 2017	US Government Accountability Office publishes a study on Open Innovation that contemplates the use of prizes.	

Source: synthesis literature.

Appendix B: Search terms used to augment initial empirical literature set

Search terms	Search date	Years range	Total result publications	Empirical prize publications	Within seed list	Other prize related	Case study related
"innovation prize*"	7/15/17	1900-2017	37	2	2	0	0
"grand challenge*" AND "innovation"	7/16/17	1900-2017	140	2	0	0	2
"grand challenge*" AND "prize*"	7/16/17	1900-2017	12	1	0	3	1
"Google Lunar X Prize" OR GLXP	7/21/17	1900-2017	23	1	1	2	11
"Ansari X Prize"	7/21/17	1900-2017	8	2	2	2	1
"Northrop Grumman Lunar Lander Challenge"	7/21/17	1900-2017	2	2	2	0	0
"DARPA Challenges" OR "DARPA Grand Challenges"	7/21/17	1900-2017	3	0	0	0	4
NASA prize*	7/21/17	1900-2017	20	1	0	1	4
DARPA prize*	7/21/17	1900-2017	12	0	0	2	7
"grand challenge*" AND reward*	7/24/17	1900-2017	10	0	0	0	0
"innovation challenge*" AND reward*	7/24/17	1900-2017	2	0	0	0	0
"government prize*"	7/27/17	1900-2017	1	0	0	0	0
"government contest*"	7/27/17	1900-2017	8	0	0	0	0
"government competition*"	7/27/17	1900-2017	42	0	0	0	0
"X Prize"	7/27/17	1900-2017	77	4	4	0	5
Wendy Schmidt Ocean Health X Prize	8/14/17	1900-2017	0	0	0	0	0
"Centennial Challenges"	8/14/17	1900-2017	8	0	0	1	0

Source: author's search using Thomson Reuters Web of Science and Google Scholar.

Appendix C: Synthesis literature

Authors	Year	Journal	Type of work	Research design	Data source type	Method	Data collection, sources	Prizes, case studies
Davis & Davis (2004)	2004	[Conference paper]	Synthesis	-	Secondary	Synthesis	Other literature on prizes, diverse online sources	Early aviation prizes, human-powered flight and SERP prizes
Macauley (2005)	2005	Space Policy	Synthesis	-	Secondary	Synthesis	Diverse sources (online) and book	Prize focus on chemistry and car, aviation, rocketry technologies. Three dozen aviation prizes, e.g. Orteig Prize, Michelin Cup
Masters (2006)	2006	[Working paper]	Synthesis	-	Secondary	Synthesis	Other literature, annecdotal accounts of the development and impact of prizes	Longitude Prize, Food Preservation Prize, Alkali Prize, Orteig Prize, Kremer Prize, CATS Prizes, Ansari X Prize, Rockefeller Foundation Prize for STD Testing, SERP Prize
Masters (2008)	2008	[Working paper]	Synthesis	-	Secondary	Synthesis	Historical prizes dataset	Dataset of prizes in Europe and North America from 1700 onwards by Knowledge Ecology International (2008)
Masters & Delbecq (2008)	2008	[Discussion paper]	Synthesis	-	Secondary	Synthesis	Historical prizes dataset	Dataset of prizes in Europe and North America from 1700 onwards by Knowledge Ecology International (2008)
Kay (2011a)	2011	R&D Management	Analysis	Qualitative, multiple embedded case study analysis	Primary, secondary	Grounded theory building; Logic modeling; Documentary analysis	Websites of competitions, entrants; blogs, forums; media coverage	Ansari X Prize, Northrop Grumman Lunar Lander Challenge
Kay (2011b)	2011	[Policy report]	Synthesis	-	Primary, secondary	Synthesis	Documentary evidence (websites of competitions, entrants) and in-depth interview with prize experts	Ansari X Prize, Northrop Grumman Lunar Lander Challenge, DARPA Challenges

Appendix C: Synthesis literature (continued)

Authors	Year	Journal	Type of work	Research design	Data source type	Method	Data collection, sources	Prizes, case studies
Adamczyk et al. (2012)	2012	Creativity and Innovation Management	Analysis	Literature meta-analysis	Primary	Bibliometric, descriptive analysis	Dataset of keyword-matched 201 publications (1959-2011) from EBSCOhost Business Source Complete, Google Scholar and Social Science Research Network	Diverse innovation, design, and idea prizes cited by the literature (36% of matched terms refer to design competitions; 25% of matched terms refer to idea competitions)
Breannan et al. (2012)	2012	[Discussion paper]	Synthesis	-	Secondary	Synthesis	Prize datasets compiled by other literature, econometric modeling	Diverse prizes from datasets McKinsey (2009), Knowledge Ecology International (2008), and InnoCentive (2010)
Brunt et al. (2012)	2012	The Journal of Industrial Economics	Analysis	Quantitative, statistical analysis	Primary	Statistical regressions	Statistical analysis on data on 1,986 awards for technological development offered by the Journal and exhibition catalogues of Royal Agricultural Society of England; data on patents from British Patent Office	Royal Agricultural Society of England awards of annual competitions between 1839 and 1939
Murray et al (2012)	2012	Research Policy	Analysis	Qualitative single case study analysis	Primary	Case study	Data from direct observation, personal interviews with participant teams and prize staff, online documents, and participant surveys	Progressive Insurance Automotive X Prize
Kay (2012a)	2012	[Book]	Analysis	Qualitative multiple embedded case study analysis, grounded theory building	Primary, secondary	Comparative, iterative case study analysis	Data gathering from websites of competitions, entrants; questionnaire to prize entrants; in-depth interview with prize and industry experts	Case studies: Google Lunar X Prize, Ansari X Prize, Northrop Grumman Lunar Lander Challenge

Appendix C: Synthesis literature (continued)

Authors	Year	Journal	Type of work	Research design	Data source type	Method	Data collection, sources	Prizes, case studies
Desouza (2012)	2012	[Policy report]	Synthesis	-	Primary, secondary	Synthesis	Documentary evidence (websites of competitions, entrants) and interview with award winners and prize experts	Select Challenge.gov competitions (e.g. DARPA Shredder Challenge, The Healthymagination Challenge, Apps for the Environment Challenge)
Mergel & Desouza (2013)	2013	Public Administration Review	Analysis	Qualitative single case study analysis	Primary	Case study	Interview with prize experts (managers of Challenge.gov); federal challenges posted on Challenge.gov	Case study: The implementation of Challenge.gov initiative
Mergel et al. (2014)	2014	[Conference paper]	Analysis	Qualitative analysis of prizes dataset	Primary	Descriptive analysis of prizes dataset	Descriptive analysis of prizes dataset	203 federal challenges posted on Challenge.gov
Hossain & Kauranen (2014)	2014	Journal of Organization Design	Synthesis		Secondary	Synthesis	The article doesn't describe data sources.	Ansari X Prizes, Archon Genomics X Prizes, Google Lunar X Prize, and the case of the X Prize Foundation itself
Gustetic et al. (2015)	2015	Space Policy	Synthesis	-	Secondary	Synthesis	Based on NASA prize case studies previously developed for conference presentation, insights from prize experts	Case studies: Six competitions part of the NASA Centennial Challenges (three of them online)
Khan (2015)	2015	Business History Review	Analysis	Historical analysis	Secondary	Historical research	Documentation on historical prizes in the U.S., U.K. and France during the early industrial period; documents from sponsor organizations	Historical prizes in the US, Britain and France during early industrialization period
Nardi et al (2016)	2016	[Book chapter]	Synthesis	-	Secondary	Synthesis	Prize reports	Case studies: RoboCup, UAV Challenges (e.g. UAV Challenge Outback Rescue), DARPA Challenges

Appendix C: Synthesis literature (continued)

Authors	Year	Journal	Type of work	Research design	Data source type	Method	Data collection, sources	Prizes, case studies
Vrolijk & Szajnfarber (2016)	2016	[Conference paper]	Analysis	Qualitative, multiple case study analysis	Primary	Comparative case studies; coding, tabulation, synthesis	In-person and phone semi-structured interviews with prize entrants in Centennial Challenges	Case studies: Centennial Challenges: 3D Printed Habitat, CubeQuest, Mars Ascent Vehicle, Sample Return Robot
Burstein & Murray (2016)	2016	Harvard Journal of Law & Technology	Analysis	Qualitative single case study analysis	Primary	Case study	In-depth field interviews with prize participants, organizers, and funders carried out during and after the competition (Nov 2009 - Jan 2011); direct observation; survey of participants	Case study: Governance of the Progressive Insurance Automotive X Prize (Auto X Prize)
Burton & Nicholas (2017)	2017	Explorations in Economic History	Analysis	Quantitative, econometric analysis	Primary	Statistical regressions (OLS)	Dataset of chronometer inventors assembled from Chronometer Makers of the World (CMW); Brunt et al. (2012) British patents dataset	Longitude Prize of the 18th c.
Liotard & Revest (2017)	2017	Technology Forecasting & Social Change	Synthesis	-	Secondary	Synthesis	Recent case studies analyzed in depth by other scholarly literature as well as illustrations found in various academic and government reports.	Ansari X Prize, GLXP, PIAXP, MIT Clean Energy Prize, DOE SunShot Prize, NGLLC, SERP prizes

Appendix D. Summary of findings on theme *Opportunity*

#	Finding	Select examples	What we do not know	Select references
4.1.1	Appropriate opportunities to use prizes depend on their focus along the process of technology development.	Scholars identify prize types based on research into recent prizes. For instance, NASA's Astronaut glove challenge (2007 & 2009) was given for technology demonstration (Gustetic et al., 2015). GLXP (2007-present) aims at commercial lunar technology development (Kay, 2012a).	• What design factors determine each type of prize. • Whether those types of prizes can be generalized to all technology sectors. • How the existence of different types of prizes affect the decision sponsors have to make at the moment of thinking of using prizes.	Davis & Davis (2004); Masters (2006); Kay (2012a); Gustetic et al. (2015)
4.1.2	The economic context of competitions affects the effectiveness of prizes.	Expert insights into the negative effect of the economic crisis of 2008 on the GLXP (Kay, 2012, p. 91)	• How influential the economic context is on the outcome of prizes. • Whether prizes can actually have positive effects on the economy as other evidence suggests.	Kay (2011a, 2012a)
4.1.3	The most appropriate use of prizes depends on whether potential solutions are known and the availability of potential solvers.	The sponsor of the Automotive X Prize faced great uncertainty when defining technical specifications of the challenge. Promoting innovation through other means to obtain the fuel efficiency level required by the prize would have been impossible (Burstein & Murray, 2016, p. 433)	• How potential solvers consider other incentives such as grants and patent protection in their decisions to enter competitions. • What the appropriate balance between using prizes as devices to gather information on potential solvers and designing them to attract certain communities is.	Masters (2006); Burstein & Murray (2016)
4.1.4	Phases of technological and industry sector development can affect the effectiveness of prizes.	Space prize entrants draw significantly on existing technologies (see, e.g., Kay, 2012a). As early 20th Century aviation prizes developed, they became less popular and other incentives further promoted the industry (see e.g., Macauley, 2005; Masters, 2006, 2008.)	• The magnitude and influence of contextual factors in the long-term use of historical prizes. • How prizes fit into broader cycles of technology and market development. • How much existing technology prize entrants draw upon in sectors other than aerospace.	Macauley (2005); Masters (2006, 2008); Masters & Delbecq (2008); Kay (2012a)
4.1.5	Legal and regulatory constraints in government limit the scope of application of prizes.	Challenge.gov prizes have focused mainly on raising awareness rather than new public good or services development (Mergel et al., 2014)	• Whether the current application of Challenge.gov prizes is the most efficient use of prizes in government and of the platform itself.	Mergel et al (2014)
4.1.6	Prizes are better suited to address technology areas for which patenting is not possible or is too expensive.	The cost of patenting in the U.K. may have led more inventors to enter prizes for agricultural development in the 18th Century (Brunt et al., 2012, p. 664).	• How the cost of patenting affects the strategic choice of potential solvers. • Whether the cost and possibility of patenting affects modern prizes.	Davis & Davis (2004); Breanan et al. (2012); Brunt et al. (2012)

Appendix E. Summary of findings on theme *Design*

#	Finding	Select examples	What we do not know	Select references
4.2.1	The appropriate combination of prize rewards (monetary and non-monetary) can maximize the efficacy of a prize.	A statistical analysis of historical prizes for agricultural implements showed a positive effect of medals more significant than that of monetary rewards (Brunt et al., 2012). Entrants revealed diverse non-monetary motivations when asked about the reasons to participate in aerospace prizes (Kay, 2011a, 2012a)	• What the relative importance of each type of incentive is across types of prizes, prize objectives, and technologies. • How important the benefits of prize participation are and how they relate to investment in prize entries. • What and how contextual factors motivate entrants.	Davis & Davis (2004); Macauley (2005); Kay (2011a, 2011b, 2012a); Brunt et al. (2012); Murray et al. (2012)
4.2.2	Contestant motivation varies across types of entrants and over time as the competition unfolds.	Questionnaires applied to entrants in recent NASA prizes showed that "platformers", or entrants who participated to expand upon or demonstrate pieces of their technology are driven by their technology pursuit and non-monetary incentives (Vrolijk & Szajnfarber, 2016)	• Whether there is a taxonomy of entrants. • What type of incentive each type of entrant needs to participate. • How contextual factors affect the motivations of different types of entrants and their decisions to enter prizes.	Kay (2011a, 2012a); Vrolijk & Szajnfarber (2016)
4.2.3	The definition of the prize's target problem relates to its ability to induce incremental innovation or breakthroughs.	A synthesis of early 20th Century aviation prizes literature shows that by making feats increasingly difficult, induced incremental progress and helped jumpstart the industry (Macauley, 2005)	• The causal model that explains how specific design parameters lead to the certain outcomes. • How contextual factors influenced the effect of historical prizes. • Whether multi-year prizes induce incremental change or their effect fades away.	Macauley (2005); Kay (2011b); Hossain & Kauranen (2014); Nardi et al. (2016)
4.2.4	The problems tackled by prizes cannot be defined in terms of discrete, static dimensions.	Prize expert insights into and assessment of the design and evolution of the Progressive Insurance Automotive X Prize showed that only a fuzzy, flexible definition of the prize challenge was possible (Murray et al., 2012).	• What the best method is to define prize targets. • How prize targets need to be defined to respond to changing conditions. • What are the most appropriate metrics of achievement in different kinds of prizes.	Murray et al. (2012)
4.2.5	Panels of judges with external members increase awareness and interest in prizes.	Challenge.gov competitions such as the Department of Commerce's Business Apps competition included a judging panel comprised of notable people to attract a larger audience (Desouza, 2012; p. 27)	• What the effects of ill-defined judge panels are.	Desouza (2012)
4.2.6	Regulatory and administrative processes prolong government prize design times.	Interviews with prize experts found that internal adjustments and vetting processes in Chalenge.gov prizes prolong their design times because of the public character of the platform (Mergel & Desouza, 2013).	• How to streamline internal adjustment and vetting processes to shorten prize design times.	Mergel & Desouza (2013)

Appendix F. Summary of findings on theme *Governance*

#	Finding	Select examples	What we do not know	Select references
4.3.1	Prize entrant activities draw significantly on external resources.	A bibliometric analysis of prize literature showed found links between the entrant activity topic and diverse external technological, financial, emotional, and social resources (Adamczyk et al., 2012).	• How historical contexts affected the process of gathering resources by prize entrants. • The value and importance of each type of resource ex-ante to inform prize design. • How the uneven distribution of resources affect competitions. • How to properly determine progress payments.	Masters (2006); Adamczyk et al. (2012); Kay (2012a); Burton & Nicholas (2017)
4.3.2	Prize adaptation during runtime increases the chances of prize program success.	The study of the Progressive Automotive X Prize showed that frequent rule changes gave flexibility to the competition and helped maintaining many teams in the competition (Murray et al., 2012; Liotard & Revest, 2017).	• What the appropriate balance between specific, concrete rules defined ex-ante and flexible, changing rules is. • How to anticipate the need or prepare for change.	Murray et al. (2012); Liotard & Revest (2017)
4.3.3	The cost of a prize program can significantly exceed the cash purse.	An interview with a prize expert shows that the total cost of the DARPA Challenges was twice as much as the prize monetary reward (Kay, 2011b).	• How sponsors can make prizes more cost-efficient. • How much cost components vary across types of prizes. • What conditions make prizes more cost-efficient compared to other incentives.	Kay (2011b); Brunt et al. (2012); Gustetic et al (2015)
4.3.4	Strategic announcement can increase prize effectiveness.	Interviews with prize experts show that the strategic announcement of the Google Lunar X Prize at a certain venue helped attract a community of interest for the sponsor (Kay, 2012a).	• How announcement parameters can be set for maximum effectiveness. • How these parameters vary across types of competitions. • What the role of social media is in prize announcement.	Kay (2011a, 2012a)
4.3.5	Active participation and the formation of communities can sustain the effect of prizes over time.	Based on a bibliometric analysis of prize literature, Adamczyk et al. (2012) concluded that sustainability of prize effects over time depends on active, perceived participation of contestants and formation of a community.	• Whether the formation of communities is a characteristic of prizes or needs promotion. • What forms of engagement are ideal in each type of prize. • How contestant participation evolves during the competition.	Adamczyk et al. (2012), Kay (2012a)
4.3.6	Knowledge sharing between teams can be induced to have more intense, effective competitions.	Synthesis of literature on a number of robotics prize cases such as UAV Challenges and DARPA Challenges found that gently enforced openness in competitions keeps them competitive (Nardi et al., 2016)	• What the most appropriate methods to induce or enforce knowledge sharing are. • How significant this phenomenon and its effect are.	Nardi et al. (2016)

Appendix G. Summary of findings on theme *Outcome*

#	Finding	Select examples	What we do not know	Select references
4.4.1	Prizes can induce and accelerate innovations over and above what would have occurred anyway.	A synthesis on the effect of early 20th Century aviation prizes concluded that prizes jumpstarted the aviation industry (Macauley, 2005). Other historical analysis found that the value of inventions induced by historical prizes might have not been as significant (Khan, 2015). Data on the technologies developed by entrants in aerospace prizes shows novel designs and R&D processes (Kay, 2011a).	• How external factors played out in the effect of historical prizes. • How concrete design factors connect with types and magnitude of outcomes. • How alternative prize designs or prizes associated with different points along the innovation pathway relate to ongoing and new R&D processes.	Macauley (2005); Masters (2006); Kay (2011a); Khan (2015); Nardi et al. (2016); Vrolijk & Szajnfarber (2016); Liotard & Revest (2017)
4.4.2	Prizes benefit both sponsors and entrants regardless of the final result of competitions.	A study of the DARPA Challenges and other recent prizes based on interviews with prize experts and documentary analysis found that prize managers, for example, learnt much about technological approaches to solve technical problems in autonomous vehicles and technological possibilities by comparing technologies developed by prize participants (Kay, 2011b).	• How to design prizes with concrete, achievable and measurable objectives that also maximize the benefits obtained by sponsors and entrants. • How the diverse benefits of prizes can be measured and aimed for in prize designs. • How learning by comparison occurs in practice. • How important is to award the prize to accomplish prize objectives.	Davis & Davis (2004); Kay (2011b, 2012a); Murray et al. (2012); Gustetic et al (2015); Nardi et al. (2016)
4.4.3	Prizes have a signaling effect on resource allocation.	The econometric analysis of Brunt et al. (2012) concluded that the Royal Agricultural Society prizes (1839-1939) signaled potentially profitable areas of technological development. However, Burton & Nicholas (2017) could not find statistically significant evidence on the influence of progress payments on the allocation of resources of entrants in the Longitude Prize.	• How significant the signaling effect is. • How signaling varies across types of prizes and technologies. • What factors (in addition to the cash purse) determine whether signaling occurs.. • How literature insights translate into concrete design parameters.	Davis & Davis (2004); Masters (2008); Masters & Delbecq (2008); Brunt et al. (2012); Kay (2012a); Khan (2015); Burton & Nicholas (2017)
4.4.4	Prizes can induce novel R&D and industry practices.	An investigation on the activities of teams participating in the GLXP, found iterative development and commercialization-oriented activities that are new to the space industry (Kay, 2012a)	• Whether this finding is valid across all types of prizes and industry sectors. • A concrete definition of "unconventional entrants" and the kind of contributions they can make.	Kay (2011a, 2012a)
4.4.5	Prize outputs may include technologies that are not adoption-ready.	The analysis of the maturity of the technologies developed in the GLXP showed that many of them are not aimed at or readily available for commercialization, deployment (Kay, 2012a).	• How prize design determines the "readiness level" of prize outputs.	Davis & Davis (2004); Kay (2012a)

4.4.6	Prizes induce knowledge diffusion.	Brunt et al. (2012) concluded that the Royal Agricultural Society prizes (1839-1939) facilitated knowledge diffusion through industry exhibitions. Other scholars studying historical prizes suggest that entrants that opt for secrecy could create barriers to diffusion (Burton & Nicholas, 2017).	• How significant knowledge diffusion is in prizes. • How this effect could vary across technologies and types of competitions, including those that are not public. • How knowledge diffusion can be induced to increase the effectiveness of prizes. • To what extent new communication means increase this effect.	Davis & Davis (2004); Brunt et al. (2012); Kay (2011a, 2011b, 2012a); Burton & Nicholas (2017)
4.4.7	The ability to adopt prize technologies depends on the sponsor's organizational characteristics.	Mergel & Desouza (2013), in a case study of Challenge.gov, concluded that rigid internal processes make difficult to incorporate most prize solutions into agencies' administrative processes and service offerings.	• What the organizational factors that make difficult prize result adoption are. • How prize designs can be improved to facilitate adoption of results.	Mergel & Desouza (2013)

Appendix H. Summary of findings on theme *Evaluation*

#	Finding	Select examples	What we do not know	Select references
4.5	A few empirical works offer insights into prize evaluation aspects.	Models of prizes that adopt a specific perspective (Burstein & Murray, 2016); more general models that address the prize process as a phenomenon that occurs in a certain context (Kay, 2011a, 2012a); guidelines elaborated based on direct or indirect prize experience and other literature (Conrad et al., 2017).	• What the evaluation points along the prize process are in addition to final post-prize evaluation. • What concrete measures of achievement or metrics sponsors should adopt in each kind of prize program. • What data collection points and methods sponsors should adopt along the prize process timeline.	Burstein & Murray (2016); Kay, (2011a, 2012a); Conrad et al. (2017); Kay (2011b)

Appendix I: Prize topics that have received little attention from empirical research

Aspect	What is not known	Importance	Select references
Opportunity	Potential negative effect of widespread use of prizes	Prize programs may have a limit in the number of initiatives before the incentive effect of prizes starts declining	Kay (2012b)
	In science, prizes may actually divert attention from deep intractable problems to more tractable problems	Prizes may not be suitable to promote scientific research	Zuckerman (1992)
	When a portfolio of prizes (or "subevents") is necessary	Prize initiatives tend to comprise multiple prizes announced sequentially or simultaneously	Kay (2012b); Nardi et al. (2016)
Design	How to determine the appropriate monetary and other non-monetary rewards	Not only the effectivess of prizes but also the feasibility of prize programs depend on these parameters	Davis & Davis (2004)
	Effect of periodic prizes (prize program periodic replication)	Prize effectiveness may not sustain over time in multi-year and other periodic prizes.	Adamczyk et al. (2012), Kay (2012a), Brunt et al. (2012), Nardi et al. (2016)
	Eligibility criteria, how sponsors can modify these to increase the effectiveness of prizes	This aspect of prizes can determine the cost of prize programs and whether they induce breakthroughs or other effects.	
Runtime, governance	How to support entrants' activities, funding; how the lack of upfront funding influences the activities of entrants and solutions they contribute	Prizes that pose significant challenges or long term technology development could fail if entrants do not find support for their projects.	Kay (2011a, 2012a); Adamczyk et al. (2012)
	Methods and means of engagement and "activation" during competitions	This concept relates to an important aspect of prizes which is engagement of participants and general public.	Adamczyk et al. (2012)
	Fairness of the prize process, attribution of achievements (i.e. picking the first or best performing entry).	Determines the reputation of the prize sponsor as well.	NRC (2007); Schooner & Castellano (2015)
	Collaboration and competition in prizes	Their appropriate balance could lead to more effective prizes.	
Outcome	Concrete measure or form of calculation of the total economic or societal value of prizes	This measure could help determine what the most appropriate use of prizes is.	Davis & Davis (2004)
	The effect of prizes on training, education across different levels	Prizes could represent a valuable opportunity to offer hands on training and education.	Nardi et al. (2016)
Evaluation	The appropriate methodological approach to evaluating prizes	Evaluation of prize programs is critical to understand the impact of prizes and design and execute future programs.	
	The most appropiate methods and points along the prize timeline to collect data for evaluation	Data collection is key for the evaluation of prizes.	Kay (2011b)
	The appropriate metrics to measure achievement of objectives and other benefits obtained from prize programs	Whether prize programs accomplish their objectives can only be determined if there are concrete means to measure such an accomplishment.	Kay (2011b)