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Dismantling Knowledge Boundaries at NASA: The Critical Role of Professional Identity in Open Innovation

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Abstract

Using a longitudinal in-depth field study at NASA, I investigate how the open, or peer-production, innovation model affects R&D professionals, their work, and the locus of innovation. R&D professionals are known for keeping their knowledge work within clearly defined boundaries, protecting it from individuals outside those boundaries, and rejecting meritorious innovation that is created outside disciplinary boundaries. The open innovation model challenges these boundaries and opens the knowledge work to be conducted by anyone who chooses to contribute. At NASA, the open model led to a scientific breakthrough at unprecedented speed using unusually limited resources; yet it challenged not only the knowledge-work boundaries but also the professional identity of the R&D professionals. This led to divergent reactions from R&D professionals, as adopting the open model required them to go through a multifaceted transformation. Only R&D professionals who underwent identity refocusing work dismantled their boundaries, truly adopting the knowledge from outside and sharing their internal knowledge. Others who did not go through that identity work failed to incorporate the solutions the open model produced. Adopting open innovation without a change in R&D professionals' identity resulted in no real change in the R&D process. This paper reveals how such processes unfold and illustrates the critical role of professional identity work in changing knowledge-work boundaries and shifting the locus of innovation.

Keywords: innovation, knowledge boundaries, boundary work, professional identity, open innovation, identity work, technology, work and organizations

The digital age has been changing knowledge work and the permeability of professional, organizational, and work boundaries in theoretically unexplored ways

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(Jasanoff, 2004; Leonardi and Bailey, 2008; Benner and Tushman, 2015). R&D professionals, their knowledge work, and its boundaries have been the focus of extensive studies investigating how they produce scientific and technological innovation (e.g., Tushman, 1977; Dougherty, 1992; Hargadon, 2003; Owen-Smith and Powell, 2004). Scholars have found that knowledge work boundaries play an important and contested role in collaborative R&D work, often hindering recombinant innovation (Szulanski, 1996; Carlile, 2002, 2004; Bechky, 2003a, 2003b). Professionals establish these knowledge boundaries to gain legitimacy and help distinguish experts from laypeople, as well as to distinguish between experts from different disciplines (Abbott, 1988; Lamont and Molnar, 2002). This results in the rejection of innovations proposed by individuals outside these knowledge boundaries (Barber, 1961; Campanario, 2009).

A new model of knowledge work suggests transcending these boundaries to produce innovation, an approach known as ''open,'' ''peer-production,'' or ''distributed'' innovation (Von Hippel, 1988, 2005; Chesbrough, 2003; Benkler, 2006). Opening up scientific and technological problems beyond organizational and professional boundaries holds great potential for producing recombinant innovation across disciplines (Hargadon and Sutton, 1997; Jeppesen and Lakhani, 2010; Davis, 2016). Yet prior literature has suggested that professionals would fiercely reject a model that invites outsiders to solve their scientific and technological challenges.

The history of science and technology is filled with cases of rejected innovations coming from outside the knowledge boundaries of a given professional community: from germ theory by Pasteur (a chemist, not a medical professional) to the theory of energy conservation by Helmholtz (a physician, not a physicist) to principles of inheritance from Mendel (an amateur biologist who relied on mathematics) (Barber, 1961; Campanario, 2009). Knowledge is embedded and invested in R&D professionals' work processes and practices and therefore is ''at stake'' for those actors who have developed it (Carlile, 2002). Moreover, open innovation platforms attract individuals on the margins of knowledge boundaries either socially or knowledge-wise (Jeppesen and Lakhani, 2010), posing a threat to specialized knowledge developed in an organization or a discipline. Therefore, beyond the notorious not-invented-here syndrome (Allen, 1977; Katz and Allen, 1982), R&D professionals have unique reasons for rejecting knowledge from open innovation platforms.

A growing number of organizations and professionals in various industries are experimenting with the open innovation model (Laursen and Salter, 2006, 2014; Murray and O'Mahony, 2007; Lakhani, Lifshitz-Assaf, and Tushman, 2013; Powell, 2016), but we still know very little about its use and impact. Most studies have focused on the model's platforms and communities, as well as their participants (West, 2003; O'Mahony and Ferraro, 2007; Dushnitsky and Klueter, 2010; Jeppesen and Lakhani, 2010; Arazy et al., 2016). Few studies have explored the relationship between organizations and these online platforms and communities (West and O'Mahony, 2005; Dahlander and Wallin, 2006; Henkel, 2006). The open innovation model's effect on R&D professionals and work inside organizations in particular remains puzzling and underexplored (Chesbrough, Vanhaverbeke, and West, 2014; Benner and Tushman, 2015). This study aims to help us better understand the micro foundations and forces

affecting professionals and their work boundaries as they are challenged by this new model.

THEORETICAL PERSPECTIVES

R&D Professionals' Knowledge Work

Many studies have investigated how R&D professionals' knowledge work is organized to produce scientific and technological innovation and have illustrated how the knowledge boundaries of innovation processes are important and contested (Dougherty, 1992; Carlile, 2002, 2004; Orlikowski, 2002). These boundaries can impede collaborative knowledge work and innovation (Bechky, 2003a, 2003b; Levina and Vaast, 2005, 2013; Kellogg, Orlikowski, and Yates, 2006), often leading to the rejection of innovation developed beyond them (Szulanski, 1996). The recent ''open'' or ''distributed'' innovation model has suggested that knowledge and innovation can be produced without clear knowledge boundaries; anyone can participate and bring any kind of knowledge into the process (Von Hippel, 1988, 2005; Chesbrough, 2003; Benkler, 2006). This approach was inspired by the open source software movement, which demonstrated the possibility of innovating successfully outside of traditional organizational boundaries (O'Mahony and Lakhani, 2011; O'Mahony and Ferraro, 2012). The model has since spilled over from software into a wide array of fields, with many professionals and organizations experimenting with it (Piezunka and Dahlander, 2015; Fayard, Gkeredakis, and Levina, 2016).

The sociological literature on boundary work and professions predicts that R&D professionals will reject open innovation. Ample research has described professions that establish knowledge boundaries to help distinguish a layperson from an expert (Abbott, 1988; Zerubavel, 1993; Pachucki, Pendergrass, and Lamont, 2007). Gieryn (1983), who developed the boundary-work construct, stressed that expanding, monopolizing, and protecting boundaries are at the heart of professionalization. The concept of ''knowledge-boundary work'' captures R&D professionals' actions and efforts to preserve or expand their knowledge-work boundaries (Gieryn, 1983, 1999; Lamont and Molnar, 2002; Bechky, 2003a; Carlile, 2004). In this study, I focus on the permeability of those boundaries, examining knowledge flows in and out of R&D work and how using open innovation changes these flows.

Unlike ''hiving off'' practices (Hughes, 1958), which professionals use to allocate their more-routine duties and ''dirty work'' to others (DiBenigno and Kellogg, 2014; Huising, 2015), the open innovation model threatens to deprive the profession of its most prestigious task. Individuals often enter various science and engineering professions for the challenge and prestige that come from solving difficult scientific and technological problems. Therefore, as Van Maanen and Barley (1984: 90) explained, ''Innovations which are interpreted as potentially deskilling or which might disrupt the social structure and prestige of the community as it is currently organized will be resisted and, if possible, sabotaged.''

R&D Professionals' Identity and Innovation

Studies of knowledge and innovation processes have rarely investigated the role that identity plays in innovation. Notable exceptions have included

studies on the impact of organizational-level identity on those resisting technological change (Kaplan, Murray, and Henderson, 2003; Tripsas, 2009; Benner and Tripsas, 2012), which illustrated how managers resist change and innovation when it contradicts their existing organizational identity. This study illustrates that professional identity can play a critical role in adopting innovation, or not. Opening work boundaries challenges professionals' identity, and the ability to reconstruct and refocus that identity becomes a critical mechanism for knowledge-boundary work and shifting the locus of innovation. Without ''identity work,'' there may be no true change in the knowledge work of professionals who might otherwise appear to adopt the open model.

Change in identity has been a recent focus of the identity literature as it has moved from viewing identity as a relatively stable and enduring construct to one that is more dynamic (Gioia, Schultz, and Corley, 2000; Pratt, 2012; Anteby and Wrzesniewski, 2014). Identity scholars have developed the concept of identity work to explain the ''range of activities that individuals engage in to create, present, and sustain personal identities that are congruent with and supportive of the self-concept'' (Snow and Anderson, 1987: 1348). Professional identity work has been studied as a mechanism for resolving various types of tensions related to work processes (Wrzesniewski and Dutton, 2001; Kreiner, Hollensbe, and Sheep, 2006; Elsbach, 2009). For instance, Pratt, Rockmann, and Kaufmann (2006) proposed various tactics of identity customization through which professionals construct alternative identities in response to perceived violations of their ''work-identity integrity.'' In the current study, I investigate the effects of the open innovation model on the work-identity integrity of R&D professionals as it challenges their work boundaries. Thus I bring the literature on identity threats (Elsbach, 2003; Petriglieri, 2011) and identity work (Pratt, Rockmann, and Kaufmann, 2006; Ibarra and Barbulescu, 2010) to the literature on knowledge work and innovation in this in-depth investigation of the ''being'' and ''doing'' of professionals (Wrzesniewski and Dutton, 2001; Kaplan and Tripsas, 2008).

METHODS

Research Setting

To study the influence of open innovation on R&D professionals and their work, I conducted an in-depth longitudinal study at the U.S. National Aeronautics and Space Administration (NASA), specifically at its Space Life Science Directorate (SLSD) and related units, between 2009 and 2012. The SLSD focuses on research and development in the life sciences. Its mission is to optimize human health and performance throughout all phases of spaceflight in response to risks such as radiation, bone loss, and vision impairment. My research was designed as an inductive study in a large organization across different individuals and units—similar to most studies that have looked at the impact of new technology on professionals and their work—following one organization in depth throughout the introduction of new technologies (e.g., Barley, 1986; Zuboff, 1988; Orlikowski, 2000).

I chose NASA as a field site for several reasons. First, NASA conducted a significant experiment with open innovation in 2009 by introducing its strategic R&D challenges to outsiders. Because these challenges were the key

problems that R&D professionals were working on at the time, they were deeply engaged in the experiment. They formulated the challenges for the open innovation online platforms, evaluated the proposed solutions, and chose whether to implement them. Their involvement was critical and contrasts with many organizations' open innovation initiatives, which are marketing oriented and include no interaction with or impact on the organization's core R&D process. Second, investigating R&D professionals within the same organization enabled greater control over the field and organizational environment, yielding insight into the varying experiences of open innovation. Third, various scholars (Vaughan, 1996, 2006; Majchrzak, Neece, and Cooper, 2004; Szajnfarber and Weigel, 2013; Rottner and Beckman, 2015) have studied NASA and its innovation process, enabling this study to focus on the novel change triggered by the open innovation model. Finally, the population of interest—scientists and engineers from diverse life science fields and training (physiology, toxicology, microbiology, biomedical engineering, and medicine, among others)—is similar to that of other life sciences R&D organizations, making the findings applicable elsewhere.

Data Collection

During the three-year study period (2009–2012), I collected data and conducted iterative cycles of analysis and collection, both before and after the open innovation experiment; table A1 in the Online Appendix (http://journals.sagepub.com/doi/suppl/10.1177/0001839217747876) illustrates my data collection efforts. I collected data on 98 R&D professionals—see table 1—across 28 organizational units, relying on three main sources: observations, interviews, and project work documents. My data collection was aimed at gaining a deep understanding of the day-to-day work experience of R&D professionals at NASA as a means to understanding their open innovation experience in context. Therefore, for each of the data sources detailed below, I started by collecting data on the R&D professionals' daily work and then focused on the open innovation experiment and its impact.

   Observation. To gain an in-depth understanding of the R&D work of professionals in the organization, I collected data during visits to the NASA SLSD located at Johnson Space Center in Houston, Texas, for an average of one week every other month for two years. I participated in summer training

Table 1. Demographics of R&D Professionals at NASA SLSD (N = 98)

Educational background	
Science	37 (37.8%)
Biomedical engineering	8 (8.2%)
Engineering	30 (30.6%)
Medicine	9 (9.2%)
Other	14 (14.3%)
Male	62 (63.3%)
Female	36 (36.7%)
Average age	41 (S.D. 8)
Average tenure (in years)	13 (S.D. 8)

sessions for interns, observed R&D units and labs, and shadowed their members. I also joined R&D professionals at work events—such as the annual Humans in Space conference and the last shuttle flight astronauts' return debriefing—to understand and relate to their work environment. I complemented these physical observation data with remote participation in their meetings on a regular basis. To explore the influence of the open innovation experiment on their work specifically, I observed R&D meetings, attended project demonstrations, and joined off-site meetings with potential collaborators (General Electric) and contractors (Wyle Laboratories). I observed all the open innovation workshops and meetings and attended NASA's first open innovation workshop with the White House Office of Science and Technology. I received permission to record my observations (later transcribed) and also took handwritten notes, resulting in approximately 1,000 pages of field notes.

Interviews. I conducted semi-structured interviews with R&D professionals who varied in their level of participation in open innovation processes and in their professional backgrounds. Overall, I conducted 104 interviews: 87 formal interviews with 70 individuals and 17 informal interviews with 12 individuals; I interviewed key interviewees at multiple points across time. Initially, I followed a broad interview guideline aimed at understanding interviewees' work. After a year, I built more-focused protocols around their open innovation experience (Spradley, 1979). I promised them confidentiality and received permission to digitally record the interviews. All interviews were transcribed. The interviews averaged 90 minutes each, resulting in approximately 500 pages of interview transcripts and notes.

Project work documents. Throughout the study, I gained access to relevant project work documents written and presented by the R&D professionals. I collected 94 project documents from the study period and 25 presentations from meetings and workshops, resulting in approximately 1,100 pages of material. I subscribed to and collected data from the internal e-mail list pertaining to the open innovation initiative (approximately 150 internal e-mails) and the NASA daily newsfeed that R&D professionals received (approximately 1,000 e-mails). I also collected the R&D professionals' public publications and patents. These work documents were crucial to my analysis of the change in knowledge work that took place in response to the open innovation experiment. They enabled me to analyze both whether and how external knowledge flows gained through open innovation were integrated into the R&D work, as well as the degree to which internal knowledge flows were shared with people outside the organization. In addition, I had access to internal surveys on the open innovation initiative that the NASA innovation team had conducted with 25–30 of its key professionals, which allowed me to triangulate and enrich my interview and observational data.

Secondary data sources. To gain a comprehensive understanding of the open innovation experiment, I also collected data from the three open innovation platforms on which NASA posted its R&D challenges; an overview of each platform is given in table B1 in the Online Appendix. I collected both qualitative

and quantitative data on the individuals who shared solutions through the platforms, including their professional backgrounds, geographical location, proposed solutions, and awards.

Data Analysis

I conducted an iterative process of data collection and analysis to generate a theory grounded in data (Glaser and Strauss, 1967; Miles and Huberman, 1994). This field study generated an immense amount of data, both in depth at each point in time and in breadth over time. I describe below the major building blocks of the analysis conducted throughout the study.

   Comparing the open and traditional innovation models. As data were collected before and during the open innovation experiment (2009–2010), I conducted the first exploratory analysis (Charmaz, 2006): a comparative analysis between the open innovation model and the traditional model that had been employed at NASA up until the experiment. The focus was on the process—on how the two R&D work models produced knowledge differently. I elicited the main dimensions that distinguish these two models by open coding the data (Golden-Biddle and Locke, 1997) and then aggregating first-order codes into groups.

   Analyzing the impact of open innovation on R&D professionals and their work. After the open innovation experiment was completed in 2010, and for the following two years, I conducted the second exploratory analysis (Charmaz, 2006), focusing on how the open innovation model affected the R&D professionals and their work. The experiment's success attracted much attention, opposing opinions, and tensions. The following year, some R&D professionals created dramatic changes in their work process to adopt the open innovation model, while others dismissed it completely.
   To study the impact of the open innovation model on their R&D work, I conducted an in-depth investigation of the professionals' project work (Barley and Kunda, 2001; Cohen, 2013), analyzing how scientific and technological innovation in each project was produced during this period. I focused on the knowledge flows into and out of R&D project work, which involved studying each project's documents, work, and meetings from 2010 to 2012. Using axial coding (Strauss, 1987), the analysis transitioned from a highly personalized account that consisted primarily of thick descriptions to one that was more abstract and analytical (Langley, 1999). This fine-grained analysis produced a rich categorization of the R&D professionals' divergent reactions to open innovation and their impact on the locus of innovation. This analysis also illustrated the strengths of collecting in-depth data over time; what initially seemed like adoption of open innovation by multiple R&D professionals was later revealed as feigned adoption.
   To study the divergent reactions and unearth the underlying forces (Hernes, 2014), I analyzed the sources of tensions and fragmentation among the R&D professionals. I conducted a thematic analysis (Lofland and Lofland, 1995; Charmaz, 2006) using ATLAS.ti (a qualitative data-analysis program) to code each incident or expression of tensions and arguments regarding

open innovation. This analysis revealed that most tensions revolved around the role of the R&D professionals—and deeper, around their professional identity.

Before the experiment, the R&D professionals did not talk explicitly about their identity but instead spoke extensively about R&D work and innovation. But once it was challenged and for some, threatened, it became an explicitly discussed topic. This dynamic is akin to Pratt's (2012) analogy of identity being like a car's air bag: as long as everything works well, it is taken for granted and unnoticeable until an ''accident'' happens. To analyze that taken-for-granted identity before the open innovation experiment, I conducted an analysis of what they discussed daily: innovation. I analyzed the innovation narratives through their innovation stories (Bartel and Garud, 2009), organizational ceremonies, and work environment artifacts (Czarniawska-Joerges, 1998; Lieblich, Zilber, and Tuval-Mashiach, 2008). This analysis revealed a clear hero figure: the ''innovator,'' whose professional identity was that of a problem solver. Some R&D professionals saw the open innovation model as a threat to this identity, while others discussed the need to change their identity in response to the potential of the open innovation model from being problem solvers to being solution seekers. I analyzed these conversations, documents, and interviews, coding these efforts as ''identity work'' and tracking them for the next two years. The critical role of identity work in explaining the divergent reactions to open innovation became clear, as I discuss in the Findings section.

I then conducted a cross-groups analysis of the behavior types to look for, differentiating characteristics that the literature indicated might explain the variance in reactions to the open innovation model. I explored a wide range of suggested explanations from the prior literature, such as demographic characteristics (age, gender), professional characteristics (type of profession, professional education, level of education), organizational characteristics (tenure, role in the organization, hierarchy), R&D unit, patents and publications, and the level of success in finding solutions through the open innovation model. None of these factors explained the variation in responses that I observed. But investigating the professionals' work history revealed that those who had changed their roles over the years—horizontally (across projects, units, and disciplines) and not vertically (within the same units, projects, and disciplines)—were more likely to respond positively to open innovation. Finally, I conducted a confirmatory within-group analysis of each of the reaction types, sharpening my understanding of each type of response.

FINDINGS

Before the Open Innovation Experiment

On July 20, 1969, NASA did the impossible: put a man on the moon. Doing so pushed the frontiers of science and engineering. Since then, top engineers and scientists from around the world have been drawn to work for NASA to be at the locus of new knowledge creation and innovation in space exploration. These R&D professionals led the production of innovation at NASA. This work required a high level of educational specialization and professional expertise, leading to clear knowledge boundaries between R&D professionals according to their domain expertise. Due to NASA's long tradition of collaboration and

contractual relationships with a network of public and private organizations, these professionals did not work strictly within the walls of their organization. But they chose the professionals from outside organizations with whom to share their knowledge, as well as which knowledge to bring into their R&D process from the outside. The relationship among the multiple participants in the R&D processes was clearly predefined through agreements and, often, contracts. For instance, the development of the medical devices used in space missions was a collaborative effort with well-known academics and contractors, with clear agreements detailing the type of knowledge exchanged. Before the open innovation experiment, knowledge work was produced within predefined and selectively permeable boundaries.

During the Open Innovation Experiment, 2009–2010

The open innovation experiment was initiated by the director of SLSD in 2009; he and his strategy team had focused over the previous few years on enhancing their innovative capabilities through external collaborations. When they learned about the open innovation model through executive education, they decided to experiment with it. They perceived the environment at NASA in this period to be open to such experimentation and viewed the model as a great fit with the existing strategic focus on enhancing collaboration.[1] They introduced the model to the lead scientists and engineers of their R&D groups in one of their directorate meetings, and together they decided that for one year, their existing innovation model and the open innovation model would simultaneously attack their technological and scientific R&D challenges. They chose three of the four leading global open innovation platforms: Innocentive, Yet2.com, and Topcoder (hereafter, ''the platforms''; see details in Online Appendix table B1). These platforms broadcast R&D challenges to individuals with diverse professional backgrounds and are open to anyone who wishes to join.[2] In total, NASA posted 14 R&D problems on the three innovation platforms from 11 R&D units from a variety of scientific and technological fields, including microbiology, heliophysics, mechanical engineering, radiation, material science, and medical devices; table 2 provides a detailed list. These were the most important R&D challenges for that year. NASA offered awards for winning solutions ranging from $15,000 to $30,000, which were small relative to these projects' R&D budgets.

At the same time that these challenges were posted online, NASA's professionals worked on these problems internally, as well as contracting and collaborating with domain experts from other organizations, using the traditional

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[1] In 2009, R&D professionals across NASA worked on reinvigorating and demonstrating their innovative capabilities, their efforts doubled in light of the Augustine Committee's claim that NASA's spaceflight program was on an unsustainable trajectory. Various ''innovation initiatives'' sprouted to demonstrate existing R&D capabilities. Management also encouraged bottom-up and collaborative innovation, creating ''innovation days'' and ''innovation fairs.''

[2] Individuals participate in open innovation platforms for a mix of motivations, including intrinsic motivations such as enjoyment-based intellectual stimulation and community contribution (see Franke and Shah, 2003; Boudreau, Lacetera, and Lakhani, 2011; Arazy et al., 2017) and extrinsic motivations such as reputation effects (see Lerner and Tirole, 2002; Terwiesch and Xu, 2008). For further details on each of the platforms used by NASA, see the following studies: Jeppesen and Lakhani, 2010 (Innocentive), Dushnitsky and Klueter, 2016 (Yet2.com), and Boudreau and Lakhani, 2015 (Topcoder).

Table 2. The Open Innovation Experiment

R&D problem (as posted online)	Solution	Open innovation platform
1. Improved barrier layers keeping food fresh in space	Partially solved	Innocentive, Yet2.com
2. Mechanism for a compact aerobic and resistive exercise device	Solved	Innocentive
3. Data-driven forecasting of solar events	Solved	Innocentive
4. Coordination of sensor swarms for extraterrestrial research	Partially solved	Innocentive
5. Medical consumables tracking	Partially solved	Innocentive
6. Simple microgravity laundry system	Partially solved	Innocentive
7. Augmenting the exercise experience with audiovisual inputs	Not solved	Innocentive
8. Bone imaging to assess the microstructure of ''spongy'' bone that is found in the marrow cavities of whole bones	Partially solved	Yet2.com
9. Preventing growth of and removing micro-organisms and bio-films from a potable water system	Partially solved	Yet2.com
10. Real-time analysis and reporting of water-borne micro-organisms	Not solved	Yet2.com
11. Radio protectants for humans exposed to chronic and acute radiation	Not solved	Yet2.com
12. Life on Mars: seeking ideas and protocols that can differentiate terrestrial life from indigenous exobiological life	Not solved	Yet2.com
13. Miniaturized & portable diagnostic scanning systems for remote environments	Not solved	Yet2.com
14. Medical kit optimization algorithm	Solved	Topcoder

R&D model's best practices. A comparative analysis illuminates how these two processes were fundamentally different. The traditional process holds that only domain experts can solve challenging R&D programs, while the open model is based on the premise that anyone, including individuals working outside the field, can solve challenging problems. From a boundary perspective, the boundaries of the traditional knowledge work in R&D projects are very clear and impermeable unless the professionals involved choose to selectively permeate them through contracts and collaborations. The open model is based on permeable boundaries, with no choice or control over who attempts to solve the problem or how (using what type of knowledge).

The nature of the two work processes is entirely different. At NASA, the standard R&D process was organizational and based on negotiations and repeated interactions among various professionals and NASA's organizational groups over several years: the average R&D life cycle was three to five years. The open innovation model is a distributed global and virtual process of short, fast-paced cycles—three to six months, on average—with very light involvement and interaction. The costs of standard R&D projects are typically very high and induce risk-averse approaches, whereas open innovation model costs are low and lead to an experimental approach. As NASA's professionals expressed several times at the open innovation meetings and workshops: ''[The open model is] a *whole* different way of doing business.'' Table 3 presents a summary of the comparative analysis of the two processes.

Three months after the experiment began, approximately 100 of NASA's professionals were at work on these 14 strategic challenges with their collaborators and contractors, while more than 3,000 individuals from 80 countries and various industries self-selected to work on these same problems through the open innovation platforms. Figure B1 in the Online Appendix shows the geographic spread of these participants. More than 300 solutions were

Table 3. Comparative Summary of the Open vs. Traditional Innovation Model

Process characteristics	Traditional innovation model	Open innovation model
Knowledge-work boundaries	Predefined and selectively permeable boundaries	Undefined and permeable boundaries
Process participants	Domain experts (from inside and outside the organization)	Anyone (can be anonymous)
Type of process	Organizational process, negotiation-based	Distributed virtual process, with ''light'' communication and interaction
Resources	Heavy	Relatively light
Spatial dimension	Geographically concentrated in one or few locations	Widely geographically distributed
Temporal dimension	Long R&D cycles (3–5 years)	Short R&D cycles (3–6 months)

submitted on these platforms for evaluation by NASA SLSD's R&D professionals. Each challenge had clear evaluation criteria and scientific and technological requirements that had been posted online. The proposed solutions exceeded expectations, and NASA's R&D professionals were surprised by their quality. After evaluating the solutions, R&D decided that three problems had been fully solved and six partially solved, as noted in table 2. All solutions were generated within astonishingly short timeframes, and a few even surpassed the posted criteria. As a lead scientist said, ''In general, it is known that to receive a solution for that cost [the open innovation award] would not be possible otherwise. Turnaround time for a solution like this could take *years* [under the standard R&D model].'' During the same period, the traditional processes yielded no major advances in any of the 14 R&D challenges. The speed of the open process was astounding.

One solution, in particular, became known as the ''home run'' of the open innovation experiment. The prediction of solar particle events—popularly known as solar storms—was a well-known and well-researched problem at NASA and in the global heliophysics community. Solar storms are extremely dangerous to space missions; a severe solar storm could lead to what is known as ''the ultimate blackout,'' a disruption of the earth's magnetic field that could disable satellites and the Internet, ground all aviation, silence telecommunications, and damage the electric grid. Heliophysics experts at NASA and worldwide have invested significant financial and intellectual resources in developing better solar-events forecasts. At the time, the best algorithms could predict a flare just one to two hours in advance, with 50-percent accuracy and a two-sigma confidence interval. The open innovation challenge sought an algorithm that could predict an event from four to 24 hours in advance. This problem was posted in December 2009, with an award amount of $30,000. Within three months, more than 500 individuals expressed interest in this problem, and 11 submitted solutions.

The winning submission came from a semiretired radio engineer from rural New Hampshire. His solution challenged the boundaries of the knowledge work in this field, using an approach that was completely outside the heliophysics discipline and tradition. Using ground radio–based equipment instead of the traditional satellite-based data, he created an algorithm that could forecast solar flares eight hours in advance, with 75-percent accuracy and a three-sigma confidence level—well beyond the expected result by an order of magnitude.

When the heliophysicists at NASA tested his solution, they achieved even better results: 80- to 85-percent accuracy. The head of the R&D unit that worked on this problem was stunned: ''This has spun up so fast here, and that's what has caught everyone off guard.''

These successful results of the open innovation experiment triggered a wave of excitement and positive responses—from the innovation team and SLSD management to NASA's headquarters and the White House Office of Science and Technology. The press, blogs, internal memos, and reports all extolled the ''spectacular results'' of the open innovation experiment. SLSD management and the innovation team were excited and moved forward to integrate open innovation, planning to turn the experiment into a day-to-day reality. But the challenge of integration proved far bigger than they expected.

After the Open Innovation Experiment, 2010–2012

Following the successful results of the open innovation initiative, the management and innovation team assembled a ''next steps'' workshop for all of the SLSD labs to discuss the strategic R&D challenges for 2011 and how the open innovation model could be used to solve them. But reactions to the proposed integration were far from unanimously positive. The tensions, debates, and forces unleashed that day were out of the ordinary and led to a very different trajectory than had been planned. The innovation lead described the sense of fear and discomfort in the room that day:

> When you asked [whether you have an R&D problem to share], they'd say, ''You want me to tell you what I *can't* solve?'' It was very much like they would be exposing some kind of incompetency if they told us what they can't do. . . . They thought, ''You are actually asking others [on open innovation platforms] to solve it for us.'' You can see people physically uncomfortable with it in their body language.

Some explicitly expressed being deeply professionally offended by the suggestion to adopt open innovation. Alex, a leading scientist, explained:

> Open innovation?! [*Sigh*] . . . a lot of the people come to work here certainly not because they couldn't make money elsewhere. Perhaps [they could make] even more money elsewhere and have a successful career. It's because they want the opportunity to be innovative. They want the opportunity to contribute to something that nobody's ever done before. And so this [open innovation] becomes quite a slap in the face!

In sharp contrast to these negative reactions, other R&D professionals enthusiastically praised the results of the experiment and criticized colleagues for their resistance: ''All I hear is 'I am afraid of this and afraid of that.''' These arguments were often between scientists and engineers of the same R&D lab or group or among colleagues with similar professional training, roles, and tenure in the organization. The disagreements and tension created an extremely unpleasant environment in the room. By the end of the daylong workshop, some R&D professionals stated that they wanted to continue to use the open innovation platforms for their new R&D challenges for 2011, while their colleagues either refused to discuss any of their challenges or offered marginal ones so their strategic ones would not be ''opened.''

The management and innovation team members were stunned, confused, and frustrated by the rising tensions, emotions, and fragmentation. As the strategy lead said, ''What amazed me was that even within the same group, it seems like there isn't a middle ground. Either you're with it or you don't get it at all.'' These reactions were so strong and surprising that the strategy and innovation team decided to take a step back and conduct one-on-one meetings with the lead scientists and engineers. In these conversations, R&D professionals voiced mostly technical concerns over procurement processes and legal and technical issues. Although management quickly and easily solved these problems, that did not change the divergent reactions or resistance to open innovation. The managers were puzzled and decided to keep improving the open process to make it as smooth as possible for the R&D professionals to use.

Meanwhile, in lab meetings and conversations between scientists and engineers in the months following the workshop, reactions became more explicit and clearly articulated. It became clear that the open model raised deeper issues about R&D professionals' self-perception: why they chose their profession and who they are. During this period, when I interviewed R&D professionals about the open innovation model, many responded by explaining why they joined NASA and what kept them motivated. A common response was, ''You have to understand. I came to NASA to innovate. We could have gone somewhere else and get better paid.'' The open innovation model challenged their core identity motives. This was poignantly expressed by Benjamin, a senior scientist, who described how adopting open innovation went against his professional reason for being: ''I've been attracted to places that allow you to access a problem, come up with a plan, and execute the solution . . . to be able to think and solve greater problems. If I can't do it at NASA, what is keeping me from going somewhere else?''

Before the open innovation experiment, the professional identity of scientists and engineers at NASA was not explicitly discussed in meetings or conversations. Conducting a narrative analysis of these professionals' innovation stories, work artifacts, and organizational ceremonies painted a clear picture of a heroic problem solver who attacks a challenging scientific or technological problem in an innovative way. When R&D professionals shared stories of innovation, they would always glorify and credit the specific problem solver. On the bulletin boards outside the labs and offices, research papers were posted with the names of the NASA authors highlighted. The main hall at Johnson Space Center displayed a series of ''I am an innovator'' posters with R&D professionals who had won an internal innovation contest, and scientists and engineers often proudly wore ''I am an innovator'' T-shirts to work.

This identity was rooted in the education and professional training of both scientists and engineers. Even though engineers and scientists had different approaches to solving problems, both perceived themselves as problem solvers and aspired to be great ones. That identity remained intact even when a project was conducted in collaboration or through contractors. In contrast, the open innovation model clearly demarcated their role: they posed the R&D problems, while people outside NASA worked on solving them. As Leslie, a senior life scientist, explained, ''People are more than willing to take other people's information through reading papers and going to conferences and collaborating. But in terms of making yourself vulnerable and identifying what problems you

cannot solve in your lab, it [open innovation] is such *an anathema* to what they were trained to do and what was modeled to do.''
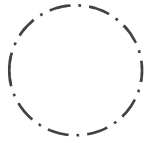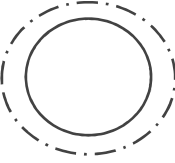
Though it was clear that open innovation deeply challenged the R&D professionals' identity, the fact that it yielded such successful results quickly prompted many scientists and engineers to question the current identity perception so tightly wed to the traditional R&D model. In one debate over open innovation, an engineer commented, ''But it's working. Isn't that what we want?'' These professionals began to explicitly discuss the need to stop identifying themselves by the methods of their work—stop focusing on how they do it but focus on why and on the drive to discover and find solutions. The shift from how to why—a refocusing of professional identity—was a very significant change. Identity refocusing entailed discarding specific professional activities and/or adopting new ones to better serve the profession's fundamental goals. The R&D professionals who began to change their identity called on others to also refocus on the ''why''—the original and broader professional goal of scientists and engineers, or what they called ''the big agenda.'' As Erik, a lead scientist, passionately contended, ''At the end of the day, it's about the *big* agenda versus the personal one. . . . Science is about finding the truth!''

A pivotal moment in the refocusing process took place in an internal SLSD work meeting, when the refocused identity was named and explicitly explained for the first time. In a discussion about the next strategic R&D challenge, a highly regarded lead scientist became frustrated with the tensions and conflicting approaches around open innovation. She intervened in the discussion and told her colleagues, ''Your main responsibility is to seek for solutions. They may come from the lab, from open innovation, or from collaboration. You should not care! You are the solution seeker!'' From that meeting on, many of her colleagues took on the identity of solution seeker. Naming the refocused identity was helpful in mobilizing the change and sparking conversations between colleagues. In meetings and workshops, they began to discuss how a solution seeker's main role is to find a solution and not necessarily be the one solving the problem. As Chris, a leading biomedical engineer, explained, it required a deep ''mindset shift'' among his colleagues who defined themselves through their work:

> It's going to take . . . a change in their heads on how they do their jobs [to adopt open innovation]. . . . Knowing how they are, they truly look at themselves as . . . the brains behind the vehicles. And they are the ones. I mean, there isn't anyone that's going to know better what they need to go do. They are the ones. That's what they do . . . and they make the best ones [vehicles].

During the next two years, two opposing and active movements arose at NASA and became evident in project meetings, collegial chats in labs, and interviews. One group strove to refocus and change the R&D professionals' identity, while the other worked to preserve and defend it. Over time, these groups argued less among themselves and simply started initiating changes in their own labs and organizational units. The scientists and engineers who sought to adopt open innovation initiated dramatic changes to the knowledge-work process. It was not clear, however, whether the successful solutions found through open innovation were being integrated into NASA's R&D work. Therefore I analyzed each of the R&D projects and the change in flows of knowledge in and out of them, which helped me identify the professionals'

Table 4. Knowledge-boundary Work Types and Implications

Type of knowledge-boundary work		Internal knowledge flows	External knowledge flows	Resulting knowledge boundaries	Boundaries illustration	Resulting locus of innovation
Dismantling knowledge boundaries (43%)	Full dismantling (13%)	Mostly open	Fully integrated	Undefined & permeable		External
	Perforating (30%)	Significantly open	Fully integrated	Semi-permeable		Distributed
Protecting knowledge boundaries (33%)	Feigned perforating (22%)	Significantly kept inside	Isolated	Feigned semi-permeable		
	Fencing (11%)	Kept inside	Kept outside	Clearly predefined & selectively permeable		Internal

knowledge-boundary work: whether or not they integrated external knowledge and opened up internal knowledge. Below, I detail the various types of knowledge-boundary work I observed and whether each led to a shift in the locus of innovation and knowledge production at NASA SLSD. In particular, I focus on the process of change in boundaries and shifts in the locus of innovation, because the prior literature would predict boundary protection. Moreover, I found that over this two-year period more R&D professionals (43 percent) were dismantling their knowledge-work boundaries than were protecting them (33 percent); the rest were not significantly involved with or influenced by the open innovation experiment.[3] Table 4 presents a summary of the boundary work types that I detail below.

Boundary Dismantling Work

Deliberately dismantling boundaries is an attempt to destroy knowledge-work boundaries to enhance the integration of external knowledge found through open innovation, thus shifting the locus of innovation from inside the

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[3] For example, in one of the labs, the lead scientist and project manager were affected by the open innovation experiment, while the system analyst and two lab technicians were not involved or affected by it during the period of this study.

organization and its traditional boundaries to outside. At NASA, this resulted in a deep change in the way that the scientists and engineers worked. Ada, an R&D professional, described the transformation: ''It is a shift from thinking 'The *lab* is my world' to 'The *world* is my lab.''' Before this change, the lab conceptually represented her entire work world; afterward, she included the outside world as the lab within which she could conduct her R&D work. The boundary dismantling work changed external and internal knowledge flows, which shifted the locus of innovation. There were two major types of knowledge-boundary dismantling work, distinguished by their intensity: ''full boundary dismantling work,'' in which professionals made an effort to completely destroy the boundaries of the R&D process; and ''boundary perforating,'' in which professionals dismantled selective parts of these boundaries.

Full boundary dismantling work. The most extreme change in response to the open innovation experiment involved an attempt to destroy all the knowledge boundaries of the standard R&D process, resulting in a complete shift of the locus of innovation from inside to outside the boundaries of NASA and its experts. Scientists and engineers engaged in this work believed that the R&D model should fully shift into an open model, replacing the internal R&D model. This boundary work was very effort- and resource-intensive. Some professionals tried to change the project work processes within their current R&D units, while others left their units to create a new unit named ''open NASA,'' completely devoting their time and resources to making this change a reality.

Internal knowledge flows. In full boundary dismantling work, R&D professionals opened up their strategic R&D challenges, inviting external solvers to tackle them. They also adopted the principles of the open source model, seeking openness and transparency throughout the full R&D process. They started by dismantling the boundaries around the data used in the R&D process, a task that required a significant amount of work. As one engineer explained, ''People say they open the data, but if no one can understand it, it's not really open data!'' Despite the work involved, these professionals insisted on opening as much data as possible. Even when encountering medical privacy issues, they found ways to open most of it in such a way that external researchers could investigate and collaborate as soon as data collection began. As Daniel, a bioengineer, explained, ''So we're opening up the evidence phase. . . . We're going to put that [evidence data] up as a wiki, so if medical students, for instance, are interested in looking at [the] heart attack incidence rate, they can give us information on what's on the outside and see the research that is going on, on all of our conditions.'' External researchers started using these data sources and reported back enthusiastically: ''I am a devoted consumer of NASA data. . . . These are the primary data sets behind my previous project, which just won the Go Big Data Challenge. Someone at NASA deserves credit for this win.''

Another telling decision in several projects was to turn the internal software development process into an open source one. This decision made the software developed by NASA's R&D professionals both open to others (allowing internal knowledge to flow out) and open to external contributions (allowing external knowledge to flow in). This was a significant shift in process. Software development at NASA had predefined process boundaries, while open source software is constantly evolving, as its contributors are often unknown and

changing. Liam, a leading engineer working on a strategic project, explained, ''At NASA you cannot even proceed unless you have a requirements document listing exactly how you're going to do [your work] . . . and it doesn't make any sense in the open source software development world.'' Taking advantage of open source software meant that new procurement and legal processes had to be created to enable software work with unknown online and often anonymous contributors.

External knowledge flows. As part of full boundary dismantling work, R&D professionals destroyed the boundaries and barriers against the integration of external knowledge. They fully utilized and integrated the knowledge found through open innovation platforms. They dedicated special attention to thinking about the day after the open innovation challenge: what to do with the solution found, how to evaluate and test it, and then how to integrate it. This led to the decision to open even the selection process of the external knowledge and not restrict it to NASA's experts; as one scientist said, ''If we only open one end of the process [i.e., seeking solutions], we will still have our bias on the other end [i.e., evaluating solutions].''

Moreover, these professionals initiated new R&D projects that were all conducted in the ''open,'' requiring them to fully orchestrate external knowledge work; these efforts came at the expense of conducting internal initiatives. Such was the development of the first international Space Apps hackathon. Hackathons, a popular format in open source communities, foster excitement and engagement around creative problem solving in a very short timeframe (usually one to two days). In line with the full boundary dismantling approach, the Space Apps hackathon had no disciplinary or geographic boundaries. One of the engineers who organized it described how difficult it was for his colleagues to grasp this approach: ''One of the most frequent questions we get for Space Apps is, 'Where will it be held?' The answer is: everywhere! There will be 50 local events and extensive virtual participation.'' This hackathon required massive preparation and orchestration. It dismantled boundaries around the development of software applications based on NASA's data, attracting more than 2,000 participants from around the world. More than 100 unique open source solutions were developed in less than 48 hours, and many continued after the event. Ever since, it has become one of the largest global hackathons, orchestrating over 25,000 people in 187 locations in 69 countries in 2017.

Resulting locus of knowledge and innovation production. The boundary dismantling work of these R&D professionals completely shifted the locus of knowledge and innovation from within NASA and its collaborators' circle to an external circle. Knowledge was produced within undefined and permeable boundaries and regularly flowed both in and out. This significant shift required new processes and knowledge infrastructures that both opened up internal knowledge processes and enabled external knowledge integration. One such infrastructure was an open wiki that several engineers built as a tool to share internal knowledge and to bring in external knowledge on a regular basis. Every member of the R&D group updated new and relevant knowledge around the strategic projects to the wiki instead of using the traditional internal documents. This wiki was automatically shared with members in three different space centers and with anyone external to NASA. As Ada, who led this initiative, explained:

> We do open innovation to say, ''Here's our knowledge-gap questions [the strategic R&D challenges for that year].'' . . . We have this wiki database where you put all your information in. . . . We go to universities, medical centers, conferences, and we'll take our gap questions, and we'll tell people about them and make contacts and collaborations, and then we put that into our wiki as well.

Finally, the shifting locus of innovation even received a physical expression in the work environment. Many of these professionals supported working from physical collaborative innovation open spaces, and some even created a new creative ''sandbox'' space for developing and testing technologies. These spaces had no boundary restrictions; anyone could work there.

   Boundary perforating work. In this boundary work, R&D professionals selectively dismantled parts of their R&D process; they created multiple ''holes'' in the boundaries of the R&D process for knowledge flows, mostly at a project's outset and before important milestones, as well as when external solutions were generated. They created a hybrid R&D process between the traditional R&D model and the open one, turning the locus of innovation to a distributed one. These professionals did not see the need to make a discrete choice between the standard or open R&D models, as they believed that doing both was possible. They claimed that no single perfect R&D model fits all R&D problems and concluded that their colleagues' debate over the best model was misguided: ''So one barrier [to adopting open innovation] . . . might be assuming that one size fits all!'' This boundary work took substantial effort. Most of these professionals worked to change the project work processes within their current R&D units, while some joined the innovation and strategy unit and devoted all their resources to making this change a reality.

   Internal knowledge flows. The open innovation experiment made many R&D professionals see their familiar work boundaries as a bubble that needed to be burst, and they opened their strategic projects to the outside world. Tom, a discipline scientist, explained, ''I always go to the right conferences and call the same three professors to see what the new technology is. [Open innovation] is a good way of getting out of that bubble and getting in a different way of thinking.'' They decided that instead of their traditional approach of starting from within NASA and going progressively outside, they should reverse the direction and start the project by opening it first. Only if an external solution were not found would they then begin an internal development process. This major shift meant that several important projects never made it to NASA's internal development process, as the solution was found outside first. Moreover, over time, these professionals explored other venues and created their own platforms beyond the accepted open innovation ones because they believed that no single R&D process was right for all R&D problems. Alan, an engineer, explained the importance of such a wide external focus:

> So that's something interesting. You put this R&D problem out there, and it can give a lot of people a false sense of, ''OK, there's nothing else out there.'' People would say, ''No. We did it on Innocentive and we didn't find anything, so it's not out there.'' But Innocentive isn't the whole world. Yet2.com isn't the whole world. . . . GE, for instance, does not look at Innocentive. So people have to realize that it's not a silver bullet.

Boundary perforating work was not easy, in particular when working on strategic R&D projects that involved power struggles and internal politics. It required repeated persuasion and communication efforts. This became very clear when a new strategic and urgent R&D challenge emerged. The initial approach was to treat it as a ''top secret,'' experts-led project. But the lead scientist, Catherine, then decided to open it for external involvement. As she described it, ''Trying to engage other folks to do that [open the strategic R&D problem] is a lot of time and is labor intensive, constantly providing the rationale. . . . Without me talking it out constantly, it is a dead fish in the water.''

External knowledge flows. R&D professionals who perforated boundaries fully utilized and integrated all the knowledge found through open innovation platforms. For instance, the open innovation experiment resulted in a new flexible graphite material that could serve as a food packaging material on long-term space missions; this material was shipped from the solver in Europe and tested at NASA's food lab. These professionals stressed the importance of treating outside knowledge with the same diligence during the quality testing process that internally developed solutions received. The blind application of quality evaluation was often their response to criticism from colleagues who rejected the open innovation model. Jennifer, an engineer, explained:

> There has to be a good reason and a good use for [open innovation]. I'll give you an example: this little ''rest'' device. It's a neat gadget, but that's all it is. . . . It didn't meet my [technological] need. However, the ''sleep'' device would meet a specific need right now. That's why it's useful, and that's why I am interested in doing it [using open innovation] and not just for the sake of [using] it.

These professionals believed that innovative ideas should be encouraged whether they originated inside or outside the organizational boundaries. As Chris, a leading biomedical engineer, explained, ''In the information age, I have to look for the best ideas regardless of where they come from and find ways to apply them in my context.'' Another engineer said, ''Without openness, this multidirectional flow of ideas is all but impossible.'' In this spirit, they developed an internal open innovation platform to increase knowledge flows among NASA's ten different space centers. They stressed that it was important to ''open [the organization] from within'' in order to get used to an open and distributed model. Over the next two years, more than 20 R&D projects' challenges across NASA were shared and solved through this platform.

Resulting locus of knowledge and innovation production. Boundary perforation work led to R&D project work with distributed loci of innovation, both inside and outside traditional NASA boundaries, sometimes even shifting between different phases of the same project. New project management tools were required to manage this dynamic and permeable R&D process. For instance, project managers developed a new decision support tool for choosing the right degree of openness for each stage of the project life cycle. They mapped the degrees of openness, ranging from closed models (in-house) and strategic partnerships (such as small business innovation research and NASA research announcements) to facilitated collaboration (such as Yet2.com), crowdsourcing (such as Innocentive), and crowd-managed processes (such as open source communities). This thoughtful hybrid approach to change was very nuanced and took over a year to fully develop and implement.

Boundary Protection Work

On the other end of the reaction spectrum, as the literature has predicted, some R&D professionals rejected the open innovation model and protected their knowledge boundaries both from external knowledge and from exposing their internal knowledge. Two major types of boundary protection work emerged: feigned boundary perforating and boundary fencing. Feigned boundary perforating was a defensive form of protection work, while boundary fencing was an offensive form because it was always accompanied by a direct attack on the open innovation model.

Feigned boundary perforating work. Feigned boundary perforating initially seemed similar to boundary perforation, but a closer investigation suggested that it was actually boundary protection. Although these R&D professionals seemed very receptive to the promise of open innovation, the solutions and knowledge that they received through open challenges were discarded and never integrated. This boundary work was easy to overlook because the professionals participated in open innovation challenges and outwardly adopted the model. But a careful examination of their knowledge work revealed that there was no real change in their R&D work; in fact, they constructed an additional boundary that isolated the external knowledge gained through open innovation platforms from being incorporated and tested, segregating it from the knowledge used in their R&D work.

Internal knowledge flows. Internal knowledge was shared very sparingly. These R&D professionals chose no strategic projects for open innovation; rather, they either chose existing peripheral projects or created new peripheral ones and then shared only the minimum knowledge required. In one group, the engineer Liam was frustrated by how the scientists and engineers around him extolled open innovation publicly but in fact opposed it. In an interview, he said, ''I thought that my objective there was to try and open source what I was working on, but ultimately that's what they said—that they want to do it—but they really did not want to.'' This decoupling of words and actions frustrated Liam. When such professionals were asked why they did not use the open innovation model to solve serious R&D challenges, they replied that open innovation was not a serious R&D process. Ian, a lead scientist, explained that using open innovation was not part of the ''real'' R&D work, and therefore he did not devote any serious thought to it:

> So, you know, we gotta do this [open] innovation thing. We only have so much time to devote to it. So we try and get something going, you know. . . . It's not like we had a big think tank to sit around and go through the various options. We quickly picked something . . . and went back to address the 12 other things we're working on.

External knowledge flows. These professionals blocked the external knowledge coming through the open innovation platforms from the experiment period in 2009 and afterward, keeping the external knowledge isolated and never integrating it into their R&D work. In their labs, they completely disregarded the open innovation solutions—the ostensible goal of their most strategic work. In one such lab, it went as far as withholding the fact that the lab was actually participating in open innovation. When other members of this lab

were interviewed, they did not know about the open innovation model, even though their lab's lead scientists were participating in it and finding relevant solutions through it. In another lab, when I asked the lead scientist about a solution found through open innovation, he responded that he simply could not find it or remember where he had placed it.

Resulting locus of knowledge and innovation production. Despite the perceived adoption of the open innovation model, the locus of innovation did not shift. Nothing had changed after the open experiment: knowledge was still produced, evaluated, and implemented inside predefined boundaries, a process that was shared only with specific collaborators and contractors.

Boundary fencing work. Some R&D professionals took an offensive stance to protect their boundaries. Beyond fencing off the knowledge gained through open innovation and not opening up internal knowledge, they explicitly rejected the open model in words and actions.

Internal knowledge flows. These professionals actively rejected any attempt to allow knowledge flows in or out of their predefined and selectively permeable boundaries. While their colleagues, feigning perforation, pretended to embrace open innovation, they made no such pretense. When asked about the successful results of the open innovation experiment, they dismissed it as unrelated to their field: ''That's a heliophysics-specific thing.'' They avoided open innovation–related work activities (e.g., workshops, meetings, and lectures) and dissuaded their colleagues from participating. One vivid example was a ''reply-all'' e-mail in which a member asked to be removed from the open innovation e-mail list, referring to it as spam: ''To whoever owns this e-mail list, Kindly remove my name from any/all lists so that I no longer receive any of this. Thank you. Sincerely, Paul. PS: To everyone else, sorry for creating even more SPAM.''

External knowledge flows. These R&D professionals intentionally blocked all external knowledge gained through open innovation, despite the fact that some solutions had substantial scientific and technological potential for their work and the space mission. This knowledge remained untouched; they did not test or implement the solutions found. Their unwillingness to integrate outside knowledge was strategic. This was apparent in an interview with Peter, a lead scientist, who in meetings gave the cost rationale for not using open innovation but in an interview expressed his worry that all his knowledge work would become open:

> I think having open source, it's kind of like a needle in a haystack. You are going to get some people who are maybe thinking about this problem somewhere else in the world, but you're going to have to separate . . . the wheat from the chaff, right? There's going to be a lot of crap floating around . . . which could be overwhelming. [Interviewer: I see. How many solutions did you evaluate?] Six or seven. [Interviewer: But six or seven, that's not a haystack, right?] Yes, but you know, I think they eventually want to have all the problems just out there in the open, you know.

Resulting locus of knowledge and innovation production. The locus of knowledge and innovation did not shift for these R&D professionals.

Knowledge work was conducted within predefined boundaries and shared only with collaborators and contractors, as in the traditional model. This was memorably expressed by Thomas, a scientist, when I asked, ''What is innovation?'' He replied with fervor, ''You see this [pointing to a big pile of scientific articles written by his group and collaborators]? Read this. This is innovation. This is research and not gimmicks [referring to open innovation].''
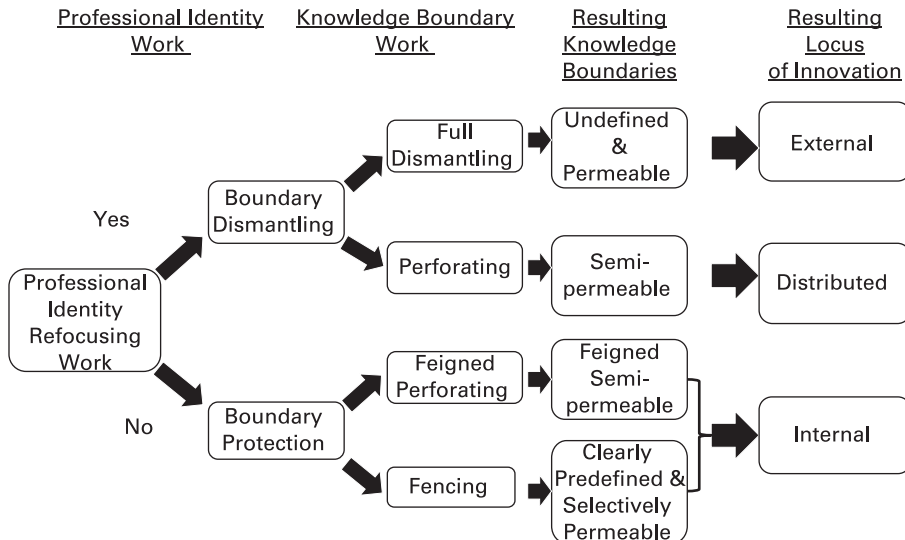
The Critical Role of Professional Identity Work

Identity work is key to understanding the forces behind the knowledge-boundary work and the adoption (or not) of the open innovation model. R&D professionals who adopted the open innovation model not only changed their knowledge-work processes and boundaries but also went through a dramatic change in their professional identity. When there was no identity work, no true change occurred in the knowledge work. Throughout the two years following the open innovation experiment, R&D professionals at one end of the reaction spectrum refocused and reconstructed their identity into that of solution seekers and abandoned any attempt to solve R&D problems on their own or with colleagues. These professionals fully dismantled their knowledge-work boundaries and adopted the open innovation model. They focused solely on searching for solutions, orchestrating the search and evaluation, and integrating the different pieces of knowledge. Laura, a lead scientist in one of the SLSD groups, in an internal presentation to colleagues, described the significance of the shift that this identity change entailed: ''A shift in fundamental assumptions. A standing fundamental assumption was that the lead researcher has direct, hands-on involvement with all aspects of the R&D activities. Instead, the new assumption is: 'The lead researcher becomes much more of an integrator, piecing the results from a wide variety of sources together.'''

   This process of identity refocusing enabled the boundary-dismantling work. In the traditional R&D model, the professional identity of problem solvers created very clear group boundaries between ''us'' and ''them,'' and only a bounded group of experts generated solutions. In becoming solution seekers, NASA's R&D professionals opened these boundaries and invited everyone to generate solutions, to be problem solvers. In refocusing their point of view, they were no longer attached to the identity of problem solver or to the use of only their own knowledge base. Their knowledge boundaries now encompassed the knowledge of outsiders. This refocusing work led them to shift their attention to the potential solvers outside of their traditional boundaries. Albert, a scientist, described this shift in a blog post, calling ''you'' (i.e., anyone) to become the next rocket scientist. He explained that the big R&D challenges no longer needed to be solved only by ''lab-coat-wearing scientists'':

> For over half a century, NASA has inspired people across the world to look to the heavens and wonder what secrets are hidden within the cosmos. Solving those mysteries has long been the domain of lab-coat-wearing scientists in government agencies and universities. However, with the advent of the Internet, social web and open source data, it has become possible for anyone to make scientific discoveries about our universe. Find out how you can actively contribute to space exploration and how the collective power of the Internet is enabling the future of scientific research.

Figure 1. The role of professional identity refocusing work on knowledge boundaries and locus of innovation.

At the other end of the reaction spectrum, R&D professionals preserved and defended their identity. They viewed open innovation as a professional insult: ''When we see opportunities like Innocentive [one of the open innovation platforms], it's extremely frustrating . . . a feeling of 'what value am I?''' Their identity as problem solvers was inseparable from their professional training and work processes, and the open innovation model fundamentally contradicted that identity. As Robert, a leading scientist and biomedical engineer, stated:

> The history of the scientific method goes against it. . . . In our training, trying to solve problems in the scientific method was: I take in all this information. I synthesize it. I do analysis and I come to some conclusion. And so to reach out to other people [through open innovation platforms] to solve it, it's like cheating!

These professionals protected their knowledge-work boundaries, rejected the open innovation model, and stressed the need to focus on the status quo. They asked management to increase internal innovation initiatives and capabilities, to dedicate more time and budget for the innovative ideas of NASA's scientists and engineers. As Matthew, a biomedical engineer, explained, ''I mean, we have to look inside, and that's a difficult thing to do . . . but the right thing to do, not just to put on paper. To truly value your internal resources and to recognize that you have plenty of innovative ideas on the inside.''

Challenging existing knowledge-work boundaries sheds light on the unexplored relationship between such boundaries and professional identity and how changing one leads to changing the other. Figure 1 summarizes the processes of professional identity work and knowledge-boundary work and their impact on the locus of innovation.[4]

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[4] This figure was created thanks to the constructive and insightful suggestions of an anonymous reviewer.

These identity work and boundary work processes were mutually reinforcing over time; they fed and strengthened each other. R&D professionals who refocused their identity from problem solvers to solution seekers dismantled their knowledge boundaries. The more boundary dismantling that took place, the more meaning, substance, and legitimacy were infused in the new role of a solution seeker, as this led to the creation of new processes and capabilities. It required building capabilities in formulating problems, searching for solutions, and evaluating and integrating knowledge. This process of change represented a deep transformation for these R&D professionals, as it went against their professional training in many ways. Marie, a bioengineer, explained the mindset shift involved: ''Changing from being a problem solver to a solution seeker is a deep philosophy change . . . It is not only about the organizations [in which we work]. This is how we have been trained ever since we [were] kids—to solve problems! To be the experts of a field and solve!''

On many projects, this two-year period of boundary dismantling and identity refocusing led to a shift in the locus of innovation that manifested in aspects of the organization beyond the project work itself. At NASA's innovation day in 2012, scientists and engineers initiated humorous games poking fun at old approaches such as ''Knowledge is Power'' and ''Not Invented Here.'' This was quite a change from 2009, when the T-shirts read, ''I Am an Innovator.'' One R&D professional explained that attitudes were changing: ''The open source mindset transfers us from the innovation-resistant 'Not Invented Here' attitude to 'Proudly Found Elsewhere.' The 'Invent-It-Ourselves' model is generally not sustainable, and it is inarguably true that the best ideas for any organization are often found outside of it.''

A remarkable example of this shift occurred in 2012 when an urgent health risk arose for the astronauts in the International Space Station. A specific medical device was needed at the station to track their health condition. Elizabeth, the medical engineer responsible for this project, spent her weekend searching for solutions, starting with general online searches, not specifically on open innovation platforms. She found a physician on YouTube who had developed such a device in his garage in a small town in the northeastern U.S. She contacted him, got the device shipped, tested it, and found it to be a creative and suitable solution for the space station. This saved significant time and development costs and quickly became a story often repeated in meetings and hallway conversations. From a narrative perspective, in contrast to the traditional innovation narratives at NASA before open innovation whereby the problem solver was the hero, now Elizabeth, a solution seeker, was the hero. She was praised for her creative and resourceful searching capabilities rather than for her raw, creative problem-solving prowess. A new narrative for innovation was born.

DISCUSSION

This study investigated the impact of the open innovation model on R&D professionals and their work. The previous literature predicted that professionals would reject external innovation and the open innovation model because they threaten the work boundaries of R&D professionals or domain experts. In contrast, this study finds divergent reactions, as open innovation challenged not only the knowledge-work boundaries of R&D professionals but also, to a great extent, their professional identity. Only the R&D professionals who refocused

their identity truly adopted the open innovation model and, in turn, changed their work processes, shifting the locus of innovation outside their traditional work boundaries. These professionals dismantled their knowledge boundaries, integrated the innovation found externally, and opened their knowledge work to the outside. In contrast, R&D professionals who did not go through identity change either feigned adoption of or explicitly rejected open innovation, reinforcing the boundaries surrounding their knowledge work and protecting their professional identities.

Knowledge-boundary Dismantling Work and the Locus of Innovation

This study sheds light on the broader question of how to organize for scientific and technological innovation (see Baldwin and Von Hippel, 2011; Benner and Tushman, 2015). The open innovation model has been proposed as a potential path to elevating innovation performance (Jeppesen and Lakhani, 2010). The results of this study suggest that the web-enabled open innovation model does introduce a real option for advancing scientific and technological knowledge. It can lead to the production of scientific and technological breakthroughs under unusually tight time and resource constraints. At the same time, open innovation poses a significant and underexplored challenge to both the knowledge-work processes and identity of R&D professionals. Adopting such a model requires a shift in both work processes and the associated professional identity. Identity is central here, as adopting open innovation methods without doing identity work resulted in no real change in the R&D process and related knowledge flows.

The shift in knowledge work found in this study—namely, boundary dismantling work—is new for R&D professionals and contradicts predictions in the literature. In Abbott's (1988) theory of professions, professionals try to gain legitimacy over tasks and problems by protecting and expanding their professional jurisdiction. As Abbott (1988: 285) explained, "The history of professions is a biography of the relationship between problems and the tasks that seek to resolve them." Professionals and experts build themselves up by legitimizing the types of problems they solve and keeping them within the boundaries of their jurisdiction. Opening up such tasks and problems to essentially anyone puts both professional jurisdiction and legitimacy at risk, contradicting the very foundations of the reigning theories of professions. Numerous studies—in particular, those on the history of scientific and technological innovation—have illustrated how professionals protect, monopolize, and strengthen their work boundaries (Sarfatti-Larson, 1979; Lamont and Molnar, 2002). For instance, Pasteur met with vehement resistance from the medical professionals of his time when he advanced his germ theory as he was a "mere" chemist (Barber, 1961). The concept of knowledge-boundary work first emerged as a description of how scientists created the first encyclopedia, deciding what qualifies as "knowledge" and should be included versus what does not and should be left out (Gieryn, 1983).

In this study, I found evidence for the persistence of such well-known protective knowledge-boundary work. I even found that such reactions are often disguised and hard to identify. Yet this study also illustrates the opposite process: scientists and engineers dismantling their knowledge-work boundaries either fully or partially to allow internal knowledge to flow out and external

knowledge to flow in, creating a path for integrating innovation derived from outside experts' domains. Unlike the historical barrage of resistance to such innovations, in this case we see a new behavior that enables their inclusion. Moreover, this study offers an important extension to previous studies that assume the permeability of boundaries to be stable and spanned only by a relatively few boundary spanners (Tushman, 1977; Heracleous, 2004; Levina and Vaast, 2005; Kellogg, Orlikowski, and Yates, 2006). I show how professionals can not only enable boundary spanning to bring external knowledge to the R&D process but also change the very nature and permeability of those work boundaries.

Studies of R&D professionals have illustrated how difficult it can be to work across such boundaries (e.g., Carlile, 2004; Levina and Orlikowski, 2009), yet crossing boundaries offers substantial potential for innovative output (Tushman and Scanlan, 1981; Rosenkopf and Nerkar, 2001; Obstfeld, 2005; O'Mahony and Bechky, 2008). This study builds on the construct of the boundary to illuminate the significance of the changes that the Internet has triggered in the nature of organizations' knowledge work (e.g., Hinds and Kiesler, 2002; Levina and Vaast, 2008; Altman, Nagle, and Tushman, 2015). It illustrates that boundaries can be dismantled and that external knowledge and innovation can be integrated into internal knowledge work, thus shifting the locus of innovation outside the traditional work boundaries of R&D organizations.

Professional Identity Work and Boundary Dismantling

The driving force behind the divergence in professionals' reactions to open innovation, explaining why some dismantle boundaries and others protect them, is identity refocusing. My findings show that professional identity work plays a critical role in cases of transformation, as professionals who reconstructed their identity were able to shift work boundaries and adopt process changes. The findings stress the importance of professionals' meaning-making activities (Weick, 1995; Wrzesniewski, Dutton, and Debebe, 2003) to their R&D work and consequently to innovation. Therefore this study contributes to the literatures on both innovation and knowledge work, which rarely investigate the role of professional identity, and to the literature on professional identity, which seldom captures the impact of identity work on professionals' work boundaries and innovation (Glynn, 2000; Elsbach and Flynn, 2013; Hatch, Schultz, and Skov, 2015).

Conceptualizing the work of professional identity refocusing contributes to our understanding of technology's impact on professionals (Abbott, 1988). Many professions arise around satisfying and solving a specific set of problems and needs, but they are often defined by the activities and tasks of the work itself rather than by the original needs. Professional identity then becomes attached to the work (Wrzesniewski and Dutton, 2001). Professional identity refocusing work decouples this attachment and brings the original need back to the center. This shift then enables boundary dismantling, allowing outsiders to perform some of the professionals' work tasks.

In this study, the R&D professionals on the two ends of the reaction spectrum were professionally and demographically similar in terms of their gender, education, and tenure. But examining their professional development histories revealed that those who changed their roles over the years—horizontally

(across projects, units, and disciplines) and not vertically (within the same projects, units, and disciplines)—were more likely to refocus their professional identity and dismantle their knowledge boundaries. This difference could explain their ability to be less attached to the *how* of their work and more able to focus on the *why*, as their *how* had changed multiple times as they shifted disciplines and projects. Further research on the ability to relax the attachment to the *how* of work and refocus on the *why* would be relevant to many professions.

Understanding professional identity refocusing work can shed light on how other professional arenas are being transformed in response to web-based work models. For instance, the professions of education and journalism are currently challenged to open their boundaries via web-based models. As professors are challenged by open education (Friedman, 2013), based on this study we can predict that professors who refocus and reconstruct their identity and capabilities will dismantle their boundaries and let external knowledge (from other professors) influence their knowledge work with their students and open their internal knowledge work (their teaching notes) to others. Such findings may not hold when professionals are working in new professions that have no notion of expertise or have not developed one yet.

This study also illustrates how professionals' identity can play a critical role in the adoption of change and innovation, expanding the existing innovation studies on organizational-level identity that have found identity to be a source of resistance to change (Kaplan, Murray, and Henderson, 2003; Kaplan and Tripsas, 2008; Tripsas, 2009; Benner and Tripsas, 2012). This study's findings support the dynamic view of identity (Gioia, Schultz, and Corley, 2000; Kreiner, Hollensbe, and Sheep, 2006; Pratt, Rockmann, and Kaufmann, 2006). It also answers the recent call to enhance our understanding of the impact of identity work and of the interplay among multiple work processes in organizations (Nelson and Lawrence, 2012; Pratt, 2012). Identity work can be an important driving force for change, and professionals can initiate and mobilize it. Furthermore, this change can have important implications beyond the involved individuals. Most of the identity work studies illustrate how it acts either as a barrier to change or as a coping mechanism to accommodate change on the individual level (see Kreiner, Hollensbe, and Sheep, 2006; Pratt, Rockmann, and Kaufmann, 2006). But professional identity work can significantly affect an outcome that exceeds the professional's scope: the production of scientific and technological innovation, with accompanying societal implications. In this sense, this study supports the proposal that identity conflict, tension, and threat can actually yield positive outcomes (Roberts, Dutton, and Bednar, 2009). It also enhances our understanding of the relationship between identity and boundaries, which so far has been conceptualized only on the organizational identity level (see Santos and Eisenhardt, 2005).

History has witnessed several shifts in the role of scientists and engineers in organizations (Merton, 1973; Bailyn and Schein, 1980; Mokyr, 2002; Shapin, 2008). This study illustrates the potential directions in which those roles may evolve in the context of open, distributed, or peer production models of innovation. It illustrates how many NASA scientists and engineers were able to mobilize a professional identity reconstruction work process across their units and within their organization in less than three years. This transformation was reflected in the change in their innovation narrative (Ibarra and Barbulescu,

2010) from a problem solver being the only hero of the innovation story to including a solution seeker as a hero figure as well. As specialization proliferates and innovation growth suffers (Jones, 2009; Gittelman, 2016), developing a solution-seeker role can be an important alternative for increasing innovative performance. Future research is warranted to understand the new capabilities that the solution-seeker role might encompass, such as formulating problems in ways that attract solvers from distant disciplines (Baer, Dirks, and Nickerson, 2013; Lifshitz-Assaf, 2018) and being able to integrate these external and distant solutions (Katila and Ahuja, 2002; Dahlander, O'Mahony, and Gann, 2014). These questions are important as part of our need to revisit and better comprehend the role of expertise in the digital age (Collins and Evans, 2007; Eyal, 2013; Lifshitz-Assaf and Szajnfarber, 2017).

The shift in the R&D professionals' role found in this study also offers important implications for innovation policy, as existing training for R&D professionals emphasizes problem solving and not solution seeking (Owen-Smith, 2001; Stern, 2004; Jones, 2010). Furthermore, current resource allocation, incentives, attribution, and award systems are aimed only at problem solvers (Jasanoff, 2004; Evans and Reimer, 2009; Murray et al., 2012). In this study, none of these systems changed. Managerial, organizational, and field pressures were similar across the units. Future research could investigate the impact of such interventions on the adoption of new innovation models. As we know that the attribution of scientific and technological innovation is at the core of R&D professionals' work (Latour and Woolgar, 1979), we must ask who gets credit (and how much) among solution seekers and external problem solvers. For instance, in 2012, Yale astronomy professors coauthored a scientific paper with the citizen scientists who had found a new planet (named PH1 after the online community of citizen scientists, Planet Hunters) based on NASA's open data. This example illustrates the rise of new attribution models to accommodate the shift in both the knowledge-production model and the role of the scientist.

Finally, this study contributes to our understanding of technology's impact on professionals and their boundaries. It demonstrates that the same technology-based intervention can be enacted differently by different individuals within a profession, thus debunking the deterministic treatment of technology as an external force and a determinant of social change (Bijker, Hughes, and Pinch, 1987). This study suggests that technology's implications for social change are best understood in how it is enacted, thus shedding light on the equivocal nature of technology (Weick, 1990). There has always been a fine line in scientific and technological knowledge between being elitist or democratic, belonging to a privileged few or empowering the masses. Technology has dramatically altered this tension and enables the democratization of knowledge. Professional, sociological, and organizational forces must now determine the direction and nature of this change.

Acknowledgments

Supplemental Material

Supplemental material for this article can be found in the Online Appendix at http://journals.sagepub.com/doi/suppl/10.1177/0001839217747876.

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