PROBLEM SOLVING BY SCIENTISTS AND ENGINEERS:
THE CONSTRUCTION OF THE ATACAMA LARGE MILLIMETER/SUBMILLIMETER ARRAY, ALMA.

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DISSERTATION ABSTRACT

Problem Solving by Scientists and Engineers:
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This dissertation asks the following research question: Which boundary spanning mechanisms affect the effective solution of problems under different organizational contexts? I draw upon problem solving and boundary spanning mechanisms literature to shed light on how communities of knowledge cope with a stream of variable and unpredictable problems under different environments. To empirically answer the research question, I focus on the conception and construction of ALMA - the "Atacama Large Millimeter Array", which is the world's largest, most expensive and most sensitive radio telescope array operating at millimeter wavelengths. I rely upon primary data based on interviews and the digital archive of entries in the knowledge-management software used by ALMA personnel to seek out and share knowledge to solve problems. I add to our understanding about how scientists and engineers employ different mechanisms to transfer and create knowledge to solve heterogeneous problems as they emerge.

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DEDICATION

To my wife, Claudia, my children, Nano and Vale and to my family. Thank you for your love, encouragement, help, and support.

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Chapter 1: Introduction

An enduring topic of research in literature of strategy and innovation is how organizations can engage in successful problem-solving activities (e.g. Allen, 1966; Simon and Newell, 1971; Lyles and Mitroff, 1980; MacDuffie, 1997; Nickerson and Zenger, 2004; Macher, 2006). In this regard, the search for an effective solution should consider how individuals involved in the problem are members of professional communities with particular approaches regarding problem-solving activities (Vincenti, 1993). A marked example of the interaction between diverse professional groups is the relationship between engineers and scientists. These are two different epistemic communities, as engineers and scientists have different ways, rules, and practices for producing techno-scientific knowledge (Knorr Cetina, 1999). As Brooks (1994) notes, science and technology evolve separately but occasionally interact (see also De Solla Price, 1965; Allen, 1984). Scientific and engineering research can be conceived as a group of beliefs that are aligned with practices that derive from distinctive search logics (Gittelman, 2016). While scientific search logic is predominantly based on forward-looking logic (Gavetti and Levinthal, 2000), engineering search logic is based on "backwards looking" (Dougherty and Dunne, 2011; Gavetti and Levinthal, 2000). Instances where science and technology interact to solve technological problems offer unique opportunities for scientific insights, and create the potential for rapid advances in technological innovation (Nelson, 2003). Unfortunately, little is known about these problem-solving occurrences, and even less is known about how engineers and scientists can collaborate effectively when working together with a common or solution-oriented goal.

Interactions between scientists and engineers occur in different environments that are constrained by specific rules, structures, incentives and practices. The scientific organizational context can be characterized by exhibiting a looser organization, with a flatter structure and with higher levels of freedom for their contributors (Stephan, 2012). All these characteristics are associated with a problem-solving approach focused on understanding, learning and more open communications between the participants engaged on problem solving activities. On the other hand, the engineering organizational context can be described by the establishment of more rigid structures, with higher reliance on hierarchy. There is less freedom, more focus on deadlines and explicit constraints in terms of time and money, associating this context with a problem-solving approach that emphasizes elements such as efficiency, speed and closer communication channels (Vicenti, 1993).

Organizational contexts influence organizational culture, work practices, and improvement of individual skills (Autio et. al, 2014). To have a better understanding of behaviors undertaken within these contexts, it is essential to acknowledge the social and historic contexts of organizations (March and Simon, 1993). Recent research on organizational contexts encourages the development of new studies by analyzing how institutional and situation-level factors act together in shaping individual activities in diverse interactions (Furnari, 2014). Innovation literature has shown that the reactions that different communities of knowledge have to specific technological advances vary largely based upon the organizational environment (Barley, 1996). There have been calls to study the role of the organizational context in the integration of scientists and engineers' knowledge (Vaughan, 1999) and to develop research on the role of organizational contexts in the micro interactions between individuals from differing systems of knowledge (Sauermann and Stephan, 2013).

Problem solving is one of those situations where scientists and engineers engage to work together. For instance, scientists can call engineers for help in solving specific problems arising from the execution of one of the instruments used in research projects (Von Hippel, 1976), or engineers can turn to scientists for insights to help them search for a solution when they are unable to find one in current knowledge (Kline and Rosenberg, 1986). Based on these diverse contexts, it might be expected that in these situations the collaborative mechanisms used by scientists and engineers to solve a problem can have different outcomes. Thus, one key challenge to joint problem-solving is the impact that organizational context can exert on problem-solving episodes, in terms of different characteristics such as organizational structure, incentives, task features, resources constraints and goals.

Innovating in areas with cutting-edge technologies requires high levels of complex knowledge (Barley and Kunda, 2001). In these situations, boundaries must be surpassed to solve problems that emerge during the development of innovation initiatives so that heterogeneous repositories of knowledge can be shared and created (Webster, 2007). Scholars in both the fields of innovation and science and technology have analyzed the mechanisms allowing the epistemic boundaries existing between scientists and engineers to be permeated to coordinate the creation and transfer of knowledge (e.g., Nochur and Allen, 1992; Tushman, 1977; Galison, 1997). Multiple mechanisms have been proposed as effective bridges, including boundary spanning individuals (Tushman, 1977; Allen, 1984; Levina and Vaast, 2005), boundary objects (Star and Griesemer, 1989; Carlile, 2004) and the emergence of a common language between the diverse communities of knowledge (Galison, 1997; Collins, Evans and Gorman, 2007). While this literature is useful and rich, literature on the existing boundaries mechanisms has generally studied only static environments. While few scholars have begun to explore the boundary dynamics between different communities of knowledge (e.g., Gorman, 2005; Rottner, 2015), how dynamic contexts enable or constrain collaboration mechanisms remains relatively unknown. Despite the importance of initiatives and projects that require collaboration between scientists and engineers, relatively little is known about what type of collaborative mechanisms are effective in problem solving, and even less explored is whether different kind of individual spanners present diverse impacts on problem-solving under different contexts. Specifically, this dissertation focuses on the role of different type of boundary spanning individuals and their contribution to increase the likelihood of fixing problems.

In this dissertation, I ask: Which boundary spanning mechanisms affect the effective solution of problems under different organizational contexts? To answer this question empirically, I focus on the conception and construction of the Atacama Large Millimeter Array, “ALMA”, the world's largest, most expensive and most sensitive radio telescope operating at millimeter wavelengths. I rely upon primary data based on a digital archive of entries in the knowledge-management software used by ALMA personnel to seek out and share knowledge in order to solve problems, dataset that is complemented with qualitative data based on fieldwork and interviews conducted by the author from 2014 to 2016. I study the period that preceded the operational launch of ALMA, from 2008 to 2014. Specifically, to illustrate what boundary spanning mechanisms are more effective to solve problems under diverse organizational contexts, I contrast problem-solving episodes occurring in two different phases of the construction of ALMA, that reflect scientific and engineering organizational phases.

The ALMA telescope array project is an example of a Big Science Project (BSP), a type of collaborative international initiative created to address fundamental scientific questions that require high levels of resources, such as time and money (Boisot, 2011). Such projects are unique in that they involve a process in which theoretical knowledge is embedded directly into design principles that yield the specifications required by scientists. This characteristic makes BSPs an excellent "natural laboratory" for studying how the interactions of scientific and technological knowledge combine to solve problems that must be resolved in the development and construction of new instruments. Likewise, during the last two decades, scholars of science and technology have recommended in-depth examination of the development of innovative instruments created by scientists and engineers working collaboratively (Rosenberg, 1994; Stephan, 2012). The design and construction of complex instruments are episodes where scientists and engineers collaborate, and can result not just in the creation of new technological knowledge but offer fresh scientific insights that emerge from experimentation with technological objects (Nelson, 2001). Complex instruments involve distributed specialized knowledge and require a high level of coordination across these specialized knowledge fields (Vincenti, 1993). They also are characterized by many unknowns, such that iterative, feedback-based learning, which is important for their development. All these elements found in Big Science Projects create a great opportunity better understand the influence of different types of collaboration mechanisms on problem-solving effectiveness, along with the effect of organizational contexts in this relationship.

Chapter 2 provides theoretical background for understanding the elements of problem formulation and problem-solving episodes occurring in organizations. Moreover, I review the literature on collaborative mechanisms between different communities of knowledge. I build on boundary spanning and knowledge networks along with problem formulating and solving research to generate propositions that argue that there are specific types of boundary spanning mechanisms that help solve problems effectively. Likewise, I draw on science and technology literature and big science project research to propose that these particular boundary-spanning mechanisms are effective for problem solving in scientific and engineering contexts, each in its own way.

Chapter 3 contains a contextual background of the Atacama Large Millimeter Array, ALMA, including its origins, the most important phases during the last 30 years implemented by the responsible people – from three continents - to build this cutting edge technology, focusing especially in the last two phases that preceded the operation launch of this big science project. Moreover, I describe the qualitative and quantitative data I collected from the ALMA organization, which includes 43 interviews with engineers, astronomers and managers involved in the construction of this telescope array and the full digital archive of entries in the knowledge-management software used by ALMA personnel to seek out and share problem-solving knowledge. Access to the site and primary archival data is a unique aspect of my research, as permission to access this information is generally difficult to acquire. Thus, I have direct insight into the problem-solving episodes that moved the project forward.

Chapter 4 provides a descriptive analysis of the data gathered at ALMA Telescope Array. Particularly, since the data is composed by a unique combination of information from interviews with a dataset that tracks the problem-solving episodes which engineers and scientists faced during the construction of ALMA, I combine descriptive statistics obtained from the quantitative dataset and the results from the interviews to give a detailed portrayal of the four primary elements that are the most relevant to my study: (1) ALMA as a complex system, (2) characteristics of problem-solving activities, (3) different organizational contexts and (4) collaboration mechanisms. For each topic, I describe how each concept presents itself and explain how analyzing each dimension individually allows a better understanding of the related characteristics and how, in some cases, constructs may be measured in the quantitative study.

Chapter 5 investigates the propositions associated to the collaborative mechanisms related to problem-solving effectiveness and different contexts explained in Chapter 2, employing the quantitative dataset from ALMA. I refine these propositions by converting them into hypotheses based in the different characteristics found at ALMA that coincide with the concepts studied in Chapter 2. Using logistic regression estimations, I compare three different boundary-spanning mechanisms on problem-solving effectiveness and contrast two different phases in this Big Science Project, which resemble scientific and engineering contexts. Overall, the results confirm that different types of boundary spanning mechanisms influence differently the likelihood of fixing a problem depending on the problem's context.

In Chapter 6, I discuss the implications of the results found in Chapter 5 to advance theory and research on the field of problem solving, boundary-spanning mechanisms and cooperation between engineering and scientific communities in the development of Big

Science Projects. Likewise, I pose the limitations of this study and the future directions that can be developed from the results of this research.

Overall, this dissertation undertakes a comparative empirical examination of problem-solving performance in innovative and scientific development, using Big Science Project as the empirical setting. I follow a process-based approach, since I am interested in studying problem-solving episodes that take place when scientists and engineers employ different boundary spanning mechanisms under scientific and engineering contexts to fix problems throughout a Big Science Project.

This dissertation aims to make three main contributions to advance problem-solving research, boundary spanning and science and technology literature. First, it contributes to the problem-solving literature by introducing particular organizational contexts, scientific and engineering, as a boundary factor to consider when establishing the better collaborative mechanisms in order to achieve effective problem-solving practices. Secondly, I examine different types of boundary spanners, depending on the type of boundary they bridge, and their impact on effective problem solving. I expand the notion of boundary spanners to: a) the boundaries individuals need to span between the activities related to the discovery of specific problems and the activities related to problem-solving that emerge overtime; b) different phases within an innovation initiative, and c) the influence on problem solving effectiveness of having higher levels of knowledge brokering in networks that are external to the problem's location. Finally, this research helps to understand the actions engineers and scientists take once they interact and solve heterogeneous problems to advance Big Science Projects.

Chapter 2: Theoretical Background and Propositions

To elaborate the propositions that will be tested in this dissertation, I first develop a theoretical background review encompassing different literatures from innovation, science and technology and strategy field, focused specifically on the following topics: problem-solving process, collaborative mechanisms, knowledge networks, scientific and engineering communities and big science projects.

2.1. Theoretical Background

2.1.1. Problem Solving

A problem occurs when an individual or organization must overcome an obstacle in order to move from a current state to a desired state (Simon and Newell, 1971). Thus, a problem arises when an individual or organization has an objective to accomplish and does not know immediately how to reach it (Baron 1988). In this sense, problem solving can be conceived as "any goal-directed sequence of cognitive operations directed to finding that unknown" (Jonassen 2004; p. 7). Consequently, problems occur when an individual or organization aims to accomplish something and does not know immediately how to do so (Baron 1988).

Problem solving are all the actions taken by either an individual or an organization to find the necessary unknown elements to solve the difficulty presented as an obstacle (Jonassen, 2004). Problem solving activities require internally representing of the problem, and at the same time, it needs the application of different streams of knowledge and search strategies to achieve the solution (Dunbar 1998; Jeppessen and Lakhani, 2010). Thus, two spaces are developed in the problem-solving process. The first one is created by the individual that found the problem, who generates an initial condition about the problem's features, and its related elements, and sets the desired outcome once the problem has been solved (Newel and Simon, 1972). The second phase is when the problem solver carries out different search strategies - chosen by him - to solve the problem, starting with the conditions and elements provided by the problem finder (Simon and Lea, 1974). Problem solving literature has suggested that problem solvers can search in multiple problem spaces, rather than the problem space offered by the problem finder (Klahr and Dunbar, 1988). It is important to note that the responsibilities for the problem solver do not necessarily stop when he or she has found a solution to the problem. The individual - or sometimes a team in charge of fixing the problem - can be responsible also of implementing the solution obtained (Nickerson, Yen and Mahoney, 2012).

Most of the efforts organizations spend on these activities are focused on the problem-solving stage (Lyles and Mitroff, 1980); ignoring that predominantly, the most important part of this process is problem formulation (Einstein and Infeld, 1938). Thus, effective problem solving activities carried by individuals and organizations should consider both the formulation and the solution of the problems. Otherwise, it is possible that either the problem solvers do not have enough information to move forward with a solution or they come up with a solution for the wrong problem (Lyles, 1990).

The selection of different problem solution spaces considers the task environment where problem-solving occurs (Kaplan and Simon, 1990). The task environment consists "…of the features of the physical environment that can either directly or indirectly constrain or suggest different ways of solving a problem" (Dunbar, 1998, page 2). Since the appropriate solution space is positively related to the problem's solution (Newel and

Simon, 1972), the specific environment where the problem was found and formulated will determine the likelihood of solving a specific problem in the organization.

The speed, efficiency, or overall successfulness of problem-solving activities can depend both on luck and the search approach utilized (Simon, 1962). Scholars from different backgrounds have worked to gain a better understanding of problem's characteristics and, in particularly, how individuals and organizations facing such situations should perform in order to be both effective and efficient in the resolution process.

Based on the seminal work of Simon (1962), complex problems have been associated with complex systems, which are entities composed by a large number of parts that interact in a complex mode (Kauffman, 1993). Building on that work over the last decade, a great deal of attention has been focused on a stream of literature addressing the so-called problem solving approach (Nickerson and Zenger, 2004). This approach's primary assumption is that solution search will vary based on the characteristics of the problem (Simon, 1962; Kauffman, 1993); such solutions will, in turn, be better deployed under specific modes of governance (Nickerson and Zenger, 2004; Felin and Zenger, 2014). This approach is rooted in both Simon's (1962) analysis of problems as complex adaptive systems and Kauffman's (1993) work on NK problem modeling. Problems can be conceptualized in terms of complexity (Simon, 1962), they either are ill or well structured (Fernandes and Simon, 1999; Macher, 2006), the degree of dispersed knowledge required (Felin and Zenger, 2014), or in terms of novelty (Haas, Criscuolo and George, 2015). In addition, it has been suggested that the use of scientific research will lead to successful solutions for complex puzzles (Fleming and Sorenson, 2004; Arora and Gambardella, 1994). Implicit in this stream of literature is the assumption that organizations have perfect knowledge on the degree of the problem's complexity prior to engaging in any kind of search for a solution, i.e. complexity is an exogenous element. However, this assumption appears invalid when applied to solving problems related to technological discovery (Nightingale, 1998; Nelson, 2003; Vincenti, 1993). In such a situation, complexity indicates a lack of understanding of the problem's elements and the interrelationships among these elements (Nightingale, 2004). This therefore makes it impossible to organize problem-solving activities based on their degree of complexity when complexity cannot be accurately assessed at the time the problem is discovered.

Moreover, implementing different types of governance structures associated with different types of problems in a search for an effective solution does not consider how the individuals involved in the problem are members of professional communities with particular approaches to facing problem solving activities (Vincenti, 1993). Thus, using governance mechanisms is not always an appropriate guide for specific modes of problem solving activities. For instance, one prominent example of the interaction between diverse professional groups is the relationship between engineers and scientists. These are two different epistemic communities because engineers and scientists have different paths, rules, and practices for producing techno-scientific knowledge (Knorr Cetina, 1999). As Brooks (1994) notes, science and technology advance in different directions but occasionally interact.

An important issue regarding problem-solving episodes is the type of search people - particularly engineers and scientists - engage in to fix problems. There are two basic forms of solution search: theory-driven and experiential search (Gavetti and Levinthal, 2000;

Gittelman, 2016). Theory-driven search is based on the notion that the use of abstract knowledge will directly help problem solvers find a solution (Fleming and Sorenson, 2004). One of the disadvantages of this approach is that when the problem is related to technological discovery, the rationality used by the theory-driven solvers is not effective. Scientific discovery progresses from known elements to an unknown output, whereas technological development may start with unclear knowledge regarding the situation, but the final output is known (Nightingale, 1998, 2004). On the other hand, experiential search requires experimentation that replicates the conditions under which the problem occurs and thus does not attempt to minimize the complexity of the problem to find its source; in turn, experiential search accept the complexity of the problem when recreating the contexts in which the problem emerges (Nelson, 2003; Thomke, Von Hippel and Franke, 1998). Thus, people involved in solution search must engage in an online learning process that recognizes that the degree of problem complexity cannot be classified beforehand (Nightingale, 1998). Based on the same foundations, major progresses in scientific knowledge have generally occurred in disciplines that are very close to engineering knowledge (Nelson, 2003). This is because science advances when it is close to experimentation and online contexts that help build new knowledge.

Another framework that contributes to explanation of how engineers and scientist approach technological problems is the chain-linked model (Kline and Rosenberg, 1986). Under this framework, the first step when engineers face a problem is to call upon current knowledge. Only when it is not possible to find the answer in the knowledge available, engineers turn to scientists for insights that can help them search for a solution. In this regard, Kline and Rosenberg’s model is consistent with Nightingale’s claims that engineers do not know whether they will need scientists to help them to solve their problems when identifying a problem. It is only when technologies have started to develop that engineers can ask scientists to assist in constructing the necessary knowledge infrastructure to allow both groups to solve their difficulties and carry on with their activities (Nightingale, 2004).

Lastly, in the last decades, scholars interested in open innovation phenomenon (e.g. Jeppesen and Lakhani, 2006; Lifshitz-Assaf, 2015), have emphasized the importance of solution-seekers. These individuals dedicate time and effort to solve problems presented by organizations interested in attracting individuals outside their organizational boundaries to help them get the critical knowledge necessary to solve their problems and move forward with their innovation and technology advances. The emergence of solution seekers as a natural consequence of the implementation of open innovation initiatives both in scientific institutions and in firms - such as the case of NASA, Procter & Gamble and Siemens (Chesbrough, 2015; King and Lakhani, 2013) - has split the typical duality inherent in the problem solving process, where there is only a problem finder and a problem solver.

2.1.2. Collaboration Mechanisms

Collaboration between scientists and engineers focused on creating scientific and technological discoveries raises different challenges regarding the possibility for individuals specialized in these dissimilar disciplines to work together (Gorman, 2012). The emergence of “trading zones,” special locations in which communities with a deep communication problem manage to collaborate effectively (Collins et. al, 2007; Kellog, Orlikowski and Yates, 2006), necessitates the use of different mechanisms that allow effective creation and transfer of knowledge across the existing boundaries between heterogeneous groups. In the following sub-sections, I describe the collaborative mechanisms that have been studied by innovation and science and technology scholars.

2.1.2.1. Boundary Spanners

A boundary can be defined as a delimitation of different activities (Gieryn, 1983). Boundaries can be established based on distinctions of place, person, discipline, cognition, and temporal/special/cultural boundaries (Carlile, 2002; Orlikowski, 2002, Rottner, 2015). Literature on innovation has explored the role of boundary spanners as a critical collaborative mechanism to advance innovation and technology outputs in organizations. Boundary spanners are defined as individuals that possess broker skills capable of integrating information and resource flows across or between organizations (Tushman, 1977; Allen, 1984). Scholars have analyzed the effectiveness of boundary spanners as bridges between interorganizational communities or different departments within a single organization (e.g. Smith and Tushman, 2005; Levina and Vaast, 2005). The main emphasis in this stream of literature has been the ability of individual boundary spanners to facilitate conversations between engineers and scientists and between basic and applied research scientists (*e.g.*, Allen, 1984; Baba, Shichijo, and Sedita, 2009; Ali and Gittelman, 2016). Results in nanotechnology, engineering and clinical fields, for instance, prove that boundary-spanning activities across different knowledge communities are related to higher levels of innovation output.

The individuals that span knowledge barriers between different groups of professionals can either be designated in advance or emerge during the collaboration process (Nochur and Allen, 1992). Qualitative studies have shown that boundary spanners that are deliberately designated by the organization with brokering responsibilities are less effective when compared to individuals who, without any hierarchy or organizational structure mandate, can generate cross boundary collaboration (DiMarco, Arin and Taylor, 2012).

Most of the literature on boundary spanners assumes that the boundaries to be bridged are static (e.g. Tushmann, 1977; Allen, 1984; Vaast and Levina, 2005). However, boundaries can be moved over time, modifying the barriers to be surpassed in order to generate effective streams of innovation (Rottner, 2015), which is critical, especially in the development and implementation of large innovation projects that require, in most of the times, many years for completion. Likewise, when individuals that prefer keeping strong boundaries to define their professional identity face alterations in those boundaries - due to new practices within their organization, such as the implementation of open innovation activities (Chesbrough, 2003) -, those individuals can re-define their professionals limits to keep their boundaries regarding people foreign to their community (Lifshitz-Assaf, 2015). This can make challenge the efforts of boundary spanners to transmit and share knowledge in the organization.

2.1.2.2. Boundary Objects and Interlanguage Mechanisms

Organization and science and technology theory have studied boundary objects as mechanisms for coordinating different communities of knowledge. A boundary object can be defined as "a set of work arrangements that are both material and processual [used as a mechanism for] cooperative work in the absence of consensus" (Star, 2010; p. 604). A boundary object can take the form of maps, spreadsheets, images and other types of concrete devices. The advantage of using boundary objects as a collaborative mechanism is that while they may have different meanings for different professional groups, their structure is recognizable by everyone engaged in the collaboration (Carlille, 2002; Star and Griesemer, 1989). Boundary objects can be present at the beginning of the interactions between dissimilar groups that are unable to communicate effectively, or can be used to share and transfer knowledge between individuals at the resolution stage of problem solving episodes (Iorio and Taylor, 2014). Like boundary spanners, organizations can designate concrete form as a collaboration facilitator, or such boundary objects may be spontaneously employed by those within the organization that are separated by any sort of boundary, be it organizational, knowledge, or technical.

Nicolini, Mengis and Swan (2011) distinguish among four different roles that objects play in allowing collaboration across disciplines: (1) there are material infrastructures that fulfill a support function for cross-community collaboration; (2) boundary objects act as translation and transformation devices across different thought worlds; (3) epistemic objects that encourage collaboration and generate mutuality among actors by reflecting what scientists and engineers do not yet know, but are working towards; and (4) activity objects that motivate collaboration and direct activities. Examples of activity objects can be the goal of building a new telescope or the development a specific drug for cancer. The theoretical relevance of this classification is that it extends the application of boundary objects to a further idea of concreteness.

It is important to recognize that boundary objects can also block cooperation if they do not have an epistemic value for at least one of the groups engaged in the collaboration (Star, 2010). Moreover, when the cooperation goal is not well defined by the different parties, boundary objects can make it more difficult to achieve a shared understanding and thus prohibit effective collaboration (Leonardi, 2011). In this sense, one of the potential avenues to explore it is to test what the performance of boundary objects under different organizational contexts.

Resolution of communication problems between disparate communities of knowledge can be developed through what Galison (1997) called interlanguage, or the creation of "in-between" vocabularies through which effective collaboration can be achieved (Collins et al., 2007). As the interaction between groups increases, the "interlanguages" change in terms of their complexity (Gorman, 2012), moving from a simple "jargon" to "pidgin" and finally developing a new language in and of itself called "creole" (Galison, 1997). At this stage, the boundaries, at least in terms of knowledge, have disappeared, as has happened with the new subfields in science that have emerged in recent decades such as nanoscience and biotechnology (Collins et al., 2003).

2.1.3. Knowledge Networks

A network can be conceptualized as a set of objects or "nodes" tied together by a set of relations, generally called links or ties (Wasserman and Faust, 1994). Part of the value that an organization is able to create comes from its participation in specific networks (Kogut, 2000). Different types of objects and information can flow from nodes to nodes through the links embedded in a network. Scholars from social networks and management fields have argued that a knowledge network is critical for organizations to achieve their goals (*e.g.* Kogut, 2000, Hansen, 1999; Ahuja, 2000). Knowledge networks can be defined as "a set of nodes— individuals or higher level collectives that serve as heterogeneously distributed repositories of knowledge and agents that search for, transmit, and create knowledge—interconnected by social relationships that enable and constrain nodes' efforts to acquire, transfer, and create knowledge" (Phelps, Heirdl and Wadhwa, 2012, p. 1,117). Research in this area shows that differences in the knowledge network's structural properties, in terms of the individual positions in the network (*e.g.*, Hansen, 2002; Gupta and Govindarajan, 2000), and the whole network structure (*e.g.*, Tsai, 2002; Shore, Bernstein, and Lazer, 2015), can enhance or impede effective intraorganizational knowledge transfer.

Another dimension that knowledge network literature has studied is the ego network structure of interpersonal ties. Scholars in this stream of literature focus on triadic closure, based on whether or not the direct contacts of a focal individual are linked to each other (e.g. Fleming, Mingo et al., 2007; Nerkar and Paruchuri, 2005). If all three nodes are connected to one another, the triad is complete. However, when two of the ego's contacts are not bound directly, a structural hole emerges (Burt, 1992). The individual that connects these two other nodes by bridging the structural hole among them is considered a boundary spanner (Burt, 2004). By connecting individuals that are not directly associated, structural hole individuals act as brokers who can obtain diverse information and knowledge in less time and more efficiently.

When considering the effect of structural holes on organizational outputs, there are two different groups of results. On the one hand, individuals who are able to connect network nodes that could not be linked without them accessing diverse network spaces. Thus, a positive relationship is expected between higher levels of structural holes and knowledge transfer (Ahuja, 2000; Burt, 2004; McFadyen, Semadeni and Canella, 2009). On the other hand, individuals without brokerage capabilities in the network are benefited by having a more dense network that can allow them to improve the willingness of their contacts to share and help them in the knowledge transfer process (Reagans and McEvily, 2003). Despite the potential for an individual to have both a greater level of structural holes and at the same time multiple strong ties with their connections, social network studies have found that since tie strength and density are positively related (Granovetter, 1983), there is a trade-off between structural diverse ego network and tie strength (Phelps, et al., 2012). Thus, in general individuals can only enjoy one of the two advantages described above.

Finally, additional research is needed on how formal and informal institutions enable and constrain knowledge networks to better understand the contingency conditions of knowledge networks (Phelps et al., 2012), due to the different influences that specific characteristics of knowledge networks have on creating and transferring knowledge to different individuals and groups, which in turn affects organizational outcomes. For instance, Morrison (2002) finds that the effect of structural holes depends on the activities sought by the individuals embedded in the network.

2.1.4. Big Science Projects

The development of Big Science Projects (BSPs) has been critical to the advancement of scientific knowledge in the twentieth century (Hevly, 1992). BSPs have three main characteristics: (1) they allow scientific communities to answer fundamental theoretical questions that are impossible to answer under "normal" scientific progress; (2) they involve collaboration between scientific and technological actors; and (3) they are international and multi-institutional in scope (Galison and Hevly, 1992; Collins, Morgan and Patrinos, 2003; Byckling et. al 2000; Hallonsten, 2012). In this sense, Big Science

Projects have emerged as solutions to fill gaps left by “normal” scientific advance in dispersed scientific communities, and serve the collective scientific enterprise. The kinds of path-breaking knowledge discoveries targeted by BSPs are directly correlated with the financial resources required for the initiatives (Autio, 2014). Important Big Science Projects implemented by the international scientific community include the Human Genome Project and the ATLAS experiment at CERN using the Large Hadron Collider (LHC) (see Collins et al., 2003 and Boisot, 2011). Big Science Projects are a useful setting to study the complex interaction of scientific and technological knowledge in the creation of highly complex instruments. A large telescope project such as ALMA is particularly useful, as McGray (2004, p. 4) points out, “the study of large telescopes is an excellent opportunity for examining the relationship between science and technology as reflected in technology design, technology development and astronomical research agendas”.

Big Science Projects, as their name indicates, are generally formed as a “project organization,” meaning that they are temporary and exist only until their specific goals have been achieved (Lundin and Söderholm, 1995; Hobday, 2000). Project organizations have particular problems for the creation and diffusion of knowledge because these temporary organizations are responsible for creating and producing high cost, complex, products and systems (Davies and Brady, 2000). Furthermore, project organizations are not isolated “islands.” On the contrary, their boundaries are permeable and can be influenced by organizations that are involved in the project (Engwall, 2003), which can blur the boundaries of the new organization. In consequence, BSPs create a unique situation for exploring how scientists and engineers collaborate under different project organizational characteristics.

"Project organization" type initiatives involve a combination of market and non-market incentives and hybrid organizational design elements. They require collaboration of public and private actors, including governments, science agencies, universities, public scientific laboratories, firm suppliers and new organizations created for the development of the project (Vuola and Hameri, 2006; Autio, 2014). In this sense, the design principles embedded in this type of initiative are different from conventional cases characterized by differences in organizational design between academic science and industrial R&D (*e.g.*, Stern, 2004; Aghion, Dewatripont and Stein, 2008). Thus, BSPs present a setting that allows the study of how organizational design principles can modify the practices of knowledge creation and diffusion.

2.1.5. Scientific and Engineering Organizational Contexts

Science and technology are generally understood as being governed by different institutional logics (*e.g.*, Gittelman and Kogut, 2003; Vincenti 1993). Thornton and Ocasio (2008) define institutional logics as "the socially constructed, historical patterns of material practices, assumptions, values, beliefs and rules by which individuals produce and reproduce their material subsistence" (p. 101). Sauermann and Stephan (2013) propose a multidimensional framework of institutional logics between industrial and academic science that can be adapted to the differences between science and technology. These authors state that four interdependent dimensions shape institutional logics in science: (1) the nature of work, (2) characteristics of the workplace, (3) characteristics of workers, and (4) the disclosure of research results. Disentangling the elements that form the base of institutional logics allows separation of the characteristics of workers that are inherent to specific communities of knowledge, such as engineers and scientists, from the characteristics of the workplace and the nature of the work, which can be related to the organizational contexts where scientists and engineers operate. By doing so, it is possible to improve our understanding regarding whether the sources of specific innovation and scientific outcomes are more influenced either by individual characteristics or by elements external to the scientists and engineers' behavior (Stephan, 2012).

Likewise, when scientists and engineers must collaborate in the development and implementation of Big Science Projects, their habits and practices are not homogeneous. However, the context where these different communities of knowledge participate will take place on either a scientific or engineering context. From a situated action perspective, which is rooted on scientific and engineering literature, individuals' actions will be affected and could be reconfigured based on the interaction with the environment (Suchmann, 1995). Consequently, when different communities of knowledge collaborate under specific contexts, the nature of work and the characteristics of the workplace will influence the approach engineers and scientists take for the effective development of tasks and the solution of specific problems (Vaughan, 1999).

The differences between the nature of work in scientific and engineering environments mainly consist in the goals that each perspective is interested in pursuing. While the nature of work in science contexts is aligned with activities focused in increasing the stock of knowledge, regardless of the usefulness these new insights might have for practical purposes (Nelson, 1959), in engineering contexts there is a greater value for advancing in solutions that can have an impact in concrete situations (Lacetera, 2009). In other words, while scientific work prefers understanding the phenomenon under study for its own sake, engineering work values the generation of knowledge as a means to an end (Allen, 1984; Brooks, 1994). Despite the fact that differences in the nature of work between these two fields are not always so large, the division of work between science and engineering to advance in innovation and scientific outputs clearly presents undeniable discrepancies (Sauermann and Stephan, 2013).

Scientific and engineering goal differences are directly related to the workplace characteristics needed to reach the objectives. First, the freedom of these individuals in these contexts varies. On the one hand, people working on science contexts have greater levels of autonomy regarding what activities, projects and problems they want to engage in (Merton, 1973). This can be seen as an organizational design response to increase the likelihood of solving problems and participating in initiatives with higher levels of uncertainty (Sauermann and Cohen, 2010). By contrast, in engineering contexts, which might be related to commercial logic, employees' freedom is restricted and the problems and initiatives to be solved are generally determined by higher organizational hierarchies (Vincenti, 1993; Aghion et al. 2008).

Secondly, the nature of work and the characteristics of the workplace in the scientific and engineering context also show differences regarding different structural dimensions. In scientific contexts, there are low levels of organizational formalization (Vaughan, 2000), which is referred to rules, procedures, and written documentation, that describe the rights and duties of employees (Walsh and Dewar, 1987; Daft, 1983). In contrast, in environments where engineering logics prevails, rules and procedures are well defined and are formally communicated throughout the organization by physical documents and formal communication channels (Vincenti, 1993).

Finally, another structural dimension showing differences between these two contexts is regarding the hierarchy of authority implemented in the organizational structure, which describes reporting duties and the control span of each supervisor (Daft, 1983). When comparing scientific and engineering contexts, hierarchies in science-based organizations are much less important than in engineering organizational environments. Overall, this characteristic reflects the degree of freedom provided to the contributors by the organization's managers.

2.2. Propositions

2.2.1. Problem Finder-Keepers on Problem Solving Effectiveness

Effective problem solving is affected when solving process is disconnected from problem finding space due to organizational barriers (Sieg, 2012; Tyre and von Hippel, 1997). If the organization does not have the adequate mechanisms, structures and incentives to make the problem formulation and problem solving flow effectively, organizational barriers will emerge, affecting the likelihood of finding a solution (Sieg, 2012; Dunbar, 1998). Moreover, if there are no effective communication channels to transmit information between these two problem stages and the problem is not well defined, individuals responsible for problem-solving will be challenged, as the problem will be too broad to identify attractive alternatives and it will also be expensive -in terms of time and energy- to attain valuable information for improving the problem's formulation.

Boundary spanning literature has established that individuals can overcome different types of barriers, including those that are characterized by separating diverse type of knowledge (Tushman, 1977; Allen, 1984; Vaast and Levina, 2005). In this sense, boundary spanners cannot only be related to bridging knowledge and information through intra and inter organizational barriers, but they can also span the existing boundaries between problem finding/formulating and problem solving spaces. I call this type of individuals 'problem finder-keeper'. These individuals are capable of connecting and transferring information and knowledge between the two most important problem-solving activities in the organization: problem finding/formulating and problem solving, by being the individual who at the same time finds the problem and is responsible of fixing it. Somehow, these individuals are 'problem keepers', since they do not hand over the problem they have found until they advance a solution.

When a problem finder-keeper is involved in problem episodes, he or she can bring information gathered from where and when the problem emerged, such as what variables could have been related to the problem's origin. This type of knowledge helps individual solvers identify better solution search strategies to accelerate and find a solution. However, as mentioned earlier, if problems are well defined and documented from the beginning and the information channels work efficiently, a problem finder-keeper will not be critical for problem solving effectiveness.

Will the problem finder-keeper equally influence problem solving effectiveness on scientific and engineering contexts or will one environment be more affected than the other? Regarding their relative influence, I expect a stronger impact from problem finder-keeper on the scientific context in comparison to engineering context. As noted earlier, scientific contexts tend to build an organizational structure characterized by procedures that are more informal and have a decentralized hierarchy (Sauermann and Stephan, 2013).

Consequently, problem finder-keeper individuals in scientific contexts might replace the procedures, rules and formalized practices lacked in this environment by connecting effectively the formulation problem process with the solution problem process.

On the other hand, in engineering contexts, the predominance of clear hierarchies and the establishment of procedures and rules that everybody within this environment must follow lead to communication channels that privilege speed and efficiency (Vincenti, 1993), helping decrease the barriers between formulation and solution spaces. Information is organized more systematically, thereby it facilitates the tracking of information required by individual to move forward with the activities.

Thus, I expect the contribution of problem finder-keeper be higher in scientific contexts because there will be fewer organizational tools that allow effective communication between the realm of problem formulation and problem solution. According to this, I make the following propositions:

Proposition 1. Problem finder-keepers positively affect problem-solving episodes in both science and engineering contexts.

Proposition 2. Problem finder-keepers influence problem-solving in science contexts more positively than in engineering contexts.

2.2.2. Phase Spanners on Problem Solving Effectiveness

Big innovation projects are composed by many stages, from idea development to the operational implementation of the initiative. People involved in these projects come from different professional communities and need to work together (Boisot, 2011; Autio, 2014). Generally, different communities of knowledge take more responsibilities in different project phases. For example, in the initial stages of Big Science Projects, scientists take the lead by engaging in negotiations regarding what scientific objectives the Big Science Project should pursue (Lundin and Söderholm, 1995). By contrast, once the scientific objectives are established, the engineering community manages the following phase by identifying the technical requirements needed to accomplish the scientific goals agreed by the scientists in the project's prior phase (Boisot, 2011). Nevertheless, although engineers run this phase, scientists must be involved, in order to secure an alignment between the scientific goal specifications and the engineering requirement phase.

Upon discovery of problems in the engineering context, participants benefit from individuals that are experienced in scientific context within the same project, for different reasons. First, individuals engaged in problem-solving activities can ask individuals who span the engineering and scientific phases to attract others who are involved in the scientific phase to help them in solving the problem, as it is highlighted by the chain-linked model proposed by Kline and Rosenberg (1985). Specifically, Kline and Rosenberg (1985) propose that when it is not possible to solve a problem emerging from engineering activities, people from scientific spaces will be asked to help in problem solving. Scientists create new knowledge that can be useful to fix problems that emerge in the engineering context. Second, innovation literature focused on user innovation, deemed as individuals that use the artifact in daily routines, states that problems related to instrumentation and scientific tools managed by engineers will have a greater likelihood of being solved if science professionals get involved (Von Hippel, 1974; Thomke, Von Hippel and Franke, 1998). Thus, if the problem solver has experience in the scientific phase of the same project, he/she will be in a better position to use information or knowledge generated in the scientific context or to contact people coming from the scientific phase that can contribute to the solution.

When problems emerge in scientific contexts, having a problem-solver from the engineering phase is useful for similar reasons. Scientific phase problem solver with prior experience in engineering contexts can provide information and knowledge produced in the engineering phase and might connect people who can be necessary to solve the problem. Overall, the existence of scientific-engineering phase spanners, defined as individuals capable of transmitting and sharing knowledge between different phases of an innovation project, will influence problem solving effectiveness in innovation and scientific and technological projects that encompass multiple phases, some scientific driven and others with an engineering profile.

Are phase spanners who participate in both science and engineering stages more important for problems occurring in science or engineering contexts? Regarding their relative influence, I expect a stronger impact from phase spanners in engineering contexts than in scientific contexts. The ability of individuals to solve problems is influenced by the individual's skills for gathering specific knowledge through the different phases of the initiative. When problems emerge in different stages of big science projects, scientists and engineers use specific sources of information that are a function of both the role developed by them and the phase of the project in which the problem is situated (Allen, 1966). In a scientific context, there is a low degree of formalization in terms of procedures, rules and actions developed by participants. In contrast, problem-solving activities taking place in engineering contexts generate more information that can be traced once the problem is solved, thanks to the higher levels of formalization in the organizational structures related to engineering environments. Information is systematized and backed up by tangible documents. These physical records might serve as inputs that can enrich the problem-solving process. This is a direct consequence of specific procedures and rules that all individuals participating in this context need to follow in order to improve the efficiency and effectiveness of the activities carried out this context. For problem-solvers in scientific contexts, it will be easier to obtain information from the engineering setting due to the prevailing degree of formalization. By contrast, engineer context problem solvers will face a more disorganized structure if they want to obtain information from the scientific side. Loose hierarchies in scientific environments will increase the difficulty of finding the right information at the right time. Thus, it suggests that phase spanners will be more valuable in problems arising in engineering contexts.

Consequently, I make the following propositions:

Proposition 3. Science-Engineering phase spanners positively affect problem-solving episodes in both scientific and engineering contexts.

Proposition 4. Science-Engineering phase spanners influence problem solving episodes on engineering contexts more positively than in science contexts.

5.2.3. Knowledge Networks on Problem Solving Effectiveness

By proposing that phase spanners influence problem solving effectiveness, I argue that there is a positive effect on problem solving activities by bridging the barriers between the scientific and engineering contexts. Even more, I expand my propositions regarding the role of boundary spanning mechanisms in external contexts by proposing that the type of structural relationships needed by the problem solver to create and maintain in the external network also influences problem solving effectiveness.

Problem solvers in scientific contexts engaged in engineering networks and problem solvers in engineering contexts engaged in scientific networks can use their structural ego network position to address different challenges in both contexts. From a structural ego network perspective (Burt, 1992), problem solvers can benefit from their structural ego position in two ways.

First, problem solvers can access a diverse range of knowledge from this cross context by possessing high levels of structural holes. Individuals who present higher degrees of structural holes are able to connect individuals throughout the network who were not previously linked (Burt, 1992; Burt, 2004). These individuals have access to diverse and rich information and knowledge from different network spaces (Nerkar and Paruchuri, 2005). Secondly, if a problem solver is unable of spanning structural holes in the cross network, he/she will instead be embedded in a dense and small network (Burt, 1992; Ahuja, 2000), which can provide other advantages for problem solving activity. Specifically, it can be easier for problem solvers to attract people from his/her condensed network, who could be more willing to share their knowledge and participate in the solution

(Levin, 1999). One of the reasons behind this behavior is that people sharing in a small and dense network will trust other member of the grid more in contrast to members involved in a more disperse network (Phelps et al. 2012; Levin and Cross, 2004; Ahuja, 2000).

Problem solvers trying to find a solution to a problem arising in an engineering context, by looking for knowledge in the scientific network should consider that in the science side the structure is disorganized and freedom is granted to their members (Stephan, 2012). Moreover, in science environments the main goal is to understand the phenomenon in study for its own sake (Merton, 1973). Based on this, engineering context problem solvers do not require to be in dense and restricted networks, since people working in this setting should not have to be very close with the problem solver to be interested in helping sharing their knowledge or directly proposing specific solution alternatives that can enhance the chances of fixing the engineering context problems. Likewise, by being in a position that span different structural holes, the problem solver can identify and transfer knowledge from different spaces from the scientific network. In this sense, I propose that by being a knowledge broker in scientific environments, the engineering solver problem have higher possibilities of fixing the problem that was assigned to solve.

Problem solvers engaged on scientific context problem solving confront a different challenge from engineering side if they want to use and obtain useful knowledge from this environment. Engineering context has a formal style of structure, where rules and procedures are well defined, the hierarchies are central for the well development and implementation of activities performed in this context and efficiency is a priority (Vincenti, 1993; Allen 1984). According to this, solvers coming from the scientific context need to be positioned in the engineering network structure privileging more dense and small networks that can make possible to attract engineering context individuals. Likewise, despite the potential advantages of being a knowledge broker by having high levels of structural holes, in the engineering context this type of condition could be not effective if people that is connected from different spaces in the engineering side are not willing to share their knowledge. Thus, I argue that for scientific context problem solvers is better to hold low levels of knowledge brokering to improve problem solving effectiveness.

Overall, I suggest the following propositions:

Proposition 5. Engineering context knowledge brokers negatively affect problem-solving episodes in scientific contexts.

Proposition 6. Scientific knowledge brokers positively affect problem-solving episodes in engineering contexts.

In summary, I propose that three different boundary-spanning mechanisms used in scientific and engineering contexts will have a distinct effect on problem solving success due to their organizational design characteristics. Specifically, I posit that problem finder-keepers, defined as individuals that can connect the practice of discovering and formulating a problem with the task of solving it, will influence problem solving effectiveness in both scientific and engineering side, but its effect will be more marked in scientific contexts, in comparison to engineering contexts. In addition, I propose that phase spanners, defined as individuals that can transmit and share knowledge between two different phases under an innovation project, will positively influence problem solving effectiveness in both scientific and engineering contexts. Moreover, I argue that phase spanners will be more relevant for problem solving in an engineering context. Finally, I propose that the knowledge-broker-capacities that a problem solver has outside the problem's context is more related to effective problem-solving in engineering environments, but will have a negative impact on problem solvers in scientific environments.

I address these propositions in the context of the construction of the Atacama Large Millimeter Array, ALMA, by examining what effects these three different boundary-spanning mechanisms have on problem solving effectiveness in two contexts found at ALMA project, which resemble science and engineering environments.

Chapter 3. The Alma Telescope Array: Main Elements and Data

In the following subsections, I describe the most important elements of the ALMA telescope array; including its origins and the phases that have had to be implemented to start begin the scientific projects for the astronomical community. Then, I explain the data I obtained to test the propositions suggested in the prior section of this dissertation.

3.2. The ALMA Telescope Array

The Atacama Large Millimeter/sub millimeter Array, known as “ALMA”, which means soul in Spanish, is the world’s largest, most expensive and sensitive radio telescope operating at millimeter wavelengths built to advance knowledge in the radio astronomy field. Radio astronomy is the study of celestial objects that give off radio waves. With radio astronomy, scientists study astronomical phenomena that are often invisible or hidden in other portions of the electromagnetic spectrum (NRAO, 2015). The main areas of research for the ALMA observatory are the origin of galaxies, the epoch of first galaxy formation and the evolution of galaxies at later stages including the dust-obscured star-forming galaxies that other large telescopes cannot see, and all phases of star and planet formation hidden away in dusty cocoons and protoplanetary disks (ESO, 2015).

The telescope is composed of 66 high-precision antennas working together at millimeter and sub-millimeter wavelengths. The ALMA telescope array is an international collaboration initiative formed by the European Organization for Astronomical Research in the Southern Hemisphere (ESO), the U.S. National Science Foundation (NSF) and the National Institutes of Natural Sciences (NINS) of Japan, in cooperation with the Republic of Chile. Likewise, the construction and operation phases of ALMA were led by ESO on behalf of the E.U. Member States; by the National Radio Astronomy Observatory (NRAO), managed by Associated Universities, Inc. (AUI), on behalf of North America; and by the National Astronomical Observatory of Japan (NAOJ) on behalf of East Asia. The Joint ALMA Observatory (JAO) provides the unified leadership and management for its construction, commissioning and operation (ALMA, 2016).

The ALMA observatory design and development phases took more than twenty years of collaborative effort by astronomers and engineers from the main partner countries, and required an investment of approximately $1.4 billion (National Science Foundation, 2014). Although the design process was centrally developed by ALMA's scientists and engineers, the selection of supplier antennas and the relationship between the selected supplier and ALMA's regional team throughout the building process were performed independently by the three main partners from the United States, Europe and Japan (ALMA, 2015). The American and European partners were responsible for twenty-five antennas each while East Asia contributed sixteen antennas.

In addition to the antennas, the main technologies needed for the ALMA telescope array are: *the front end electronics,* a receiving system capable of detecting astronomical signals in ten frequency bands; *the back end electronics,* which refer to the equipment to process the signal after reception by the receiving equipment; *the correlator,* a special-purpose digital signal hardware needed to process the signals, in pairs, from all the antennas in the array; and *the computing and software technologies*, tasked with scheduling observations on the array instruments (NRAO, 2000). Thus, ALMA presents a rare environment including multiple elements of interest for my dissertation; specifically, ALMA contains two different communities of knowledge, represented by the groups of astronomers and engineers, who had to engage in complex problem solving activities during various phases in the development, construction and operation of the observatory array.

3.2.1. The Origins of ALMA

Different possible large millimeter/sub millimeter array radio telescopes were considered by astronomy communities in Europe, North America and Japan prior to the development of the ALMA telescope (NRAO, 2000). Each community first had to agree on the scientific goals that the new radio telescope should achieve and the technologies that had to be developed to satisfy the scientific requirements.

In 1981, the National Science Foundation asked the radio astronomy community to produce a report regarding the future of millimeter-wavelength radio astronomy in the U.S. The committee called for the development of a millimeter-wave interferometer, which ultimately culminated in a proposal to the NSF in 1990 to build the Millimeter Array ("MMA"), an array of forty antennas with an estimated cost of $120 million in 1990 dollars, based on the assumption that the observatory would be located in the United States. Despite the positive reviews the proposal received, funding was not allocated for many years (NRAO, 2000).

Likewise, the idea of a large European southern millimeter array ("Large Southern Array" or "LSA") had been considered by European countries since 1991. In the middle of the 1990's, an LSA project collaboration between many institutions throughout Europe was formally established to explore potential sites, especially Chile, where such a telescope could be located, as well as to address key technological issues. The design and site LSA report was published in 1997. In the same year, an agreement between American and European institutions was reached in order to study the possibility of merging the two projects. Three aspects were analyzed in detail: scientific, technical and managerial (ESO, 2004).

A first formal memorandum was signed in 1999 by the North American community, represented by the NSF (National Science Foundation), and the European community, represented by the ESO (European Organization for Astronomical Research in the Southern Hemisphere), and in 2002, an agreement was reached to construct ALMA on a plateau in Chile (ALMA, 2015).

According to the first ALMA Director, who in 2002 was serving as the National Radio Astronomy Observatory (NRAO) Director, Paul Vanden Bout, while the scientific goals of the different telescope projects were complementary, although not identical, the primary factor behind the decision to merge the MMA and LSA was related to the costs associated with the development and construction of this scientific instrument, as it would have been impossible to obtain the required resources from only one agency.

Subsequently, Japan, through the NAOJ (National Astronomical Observatory of Japan), worked with the other partners to define and formulate its participation in the ALMA project. The official, trilateral agreement between the ESO, the NSF, and the National Institutes for Natural Sciences (“NINS”) from Japan concerning the construction of the enhanced Atacama Large Millimeter / sub millimeter Array was signed in September 2004.

The ALMA management structure was based on the concept of Integrated Product Teams (IPTs), and consisted of all individuals who were designated by one of the project’s main partners with significant responsibility for any of the following elements of ALMA: site, antennas, front end, back end, correlator, computing, system engineering and science.

The IPT management structure allowed effective coordination of the assignment of multiple tasks to various organizations utilizing different skill sets.

3.2.2. ALMA Construction and Operation Stage

Next, I describe three of the most important stages in the construction of the ALMA Telescope Array: the Assembly, Integration, and Verification stage (AIV), and the Commissioning and Science Verification phase (CSV) along with the Early Science and Full Operations.

3.1.2.1. Assembly, Integration, and Verification (AIV)

The Assembly, Integration, and Verification (AIV) stage was part of the construction phase of ALMA. The primary AIV tasks were (1) assembling and integrating the major subsystems into a functional Array Element, or "AE," meaning an ALMA antenna with all integrated instrumentation subsystems, (2) establishing initial technical performance goals, and (3) ensuring compliance with all stated technical requirements. Due to the geographically widespread manufacturer locations and transportation restrictions, final assembly and integration of the ALMA array took place at the Operations Support Facility ("OSF"), (Lopez et al., 2012). The OSF is located at an altitude of nearly 3,000 meters (984.2 feet) above sea level and 30 kilometers (37.28 miles) from the Chajnantor plateau, to which the operational antennas were subsequently moved using special transporters. The AIV phase ended in 2013 when the last antenna delivered to the Commissioning and Science Verification (CSV) team at the OSF. The AIV team was composed primarily of electrical, mechanical, computing and system engineers, and only three astronomers.

3.1.2.2. Commissioning and Science Verification (CSV)

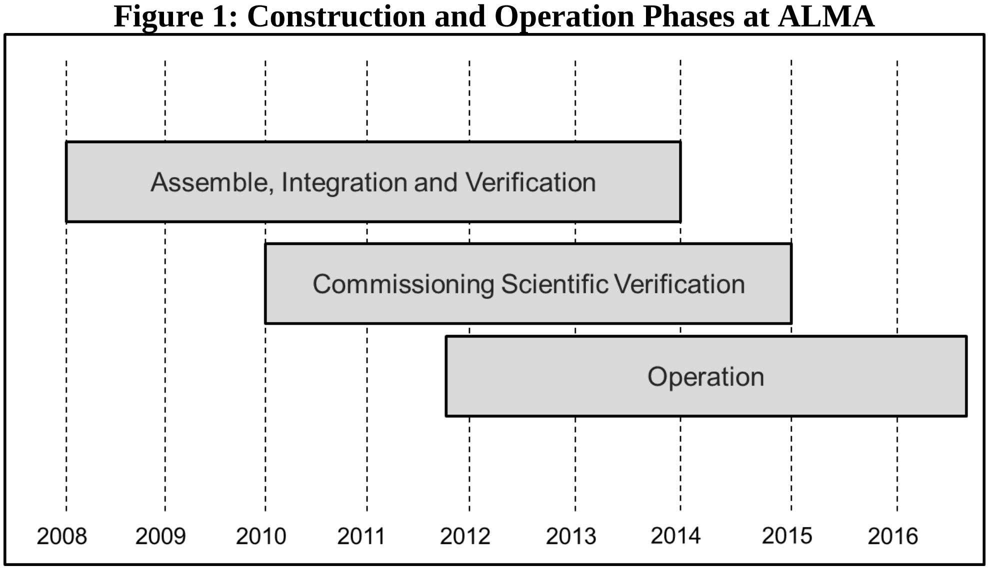
Commissioning and Science Verification (CSV) was the process, starting in 2010, by which astronomers demonstrated the validity of the data produced by ALMA. The primary mechanism for this verification was to make observations of objects that had already been observed by other telescopes and comparing those data sets with the results obtained from ALMA. When they had data sets that they considered valid, they a) released them to the community and b) the scientific capability was offered to the radio astronomy community in the next cycle of operation. Some of the requirements that the Commissioning Science Verification team tested at ALMA were related to the following performance characteristics: continuum sensitivity, line sensitivity and resolution, imaging fidelity and dynamic range, amplitude calibration accuracy and positional accuracy. The CSV team was composed by astronomers coming from the ALMA organization, the main partners (NRAO, ESO and NAOJ) and from universities and radio astronomy centers around the world.

3.1.2.3. Early Science and Full Operations

Early Science and Full Operations is the phase where the ALMA observatory began, offering observation time to the radio astronomy community. One of the programmatic goals of the ALMA construction was to begin operating the telescope as an interferometric array for scientific research as soon as possible. In 2011, the Joint ALMA Observatory (JAO) called for proposals for “cycle 0”, offering the current capacity of the Observatory at the time: a maximum of twelve antennas, three receiver bands and two array configurations. For each cycle, scientists compete for observing time by submitting proposals, which are judged based on scientific merit. Users do not travel to Chajnantor to carry out the observations. Instead, observations are dynamically scheduled, depending on weather conditions and the array configuration. The data produced during an ALMA observing run, as well as the associated calibrations, is stored in the ALMA Archive. All ALMA scientific data is subject to a proprietary period of one year from the date when they are distributed to the Principal Investigator. After this proprietary period, the data becomes public and any researcher can retrieve it by making an archive request (ALMA, 2016). In the operation activities carried out at ALMA, astronomers and engineers work together to produce the observations for the selected scientific projects.

As shown in Figure 1, these three stages were conceived consecutively and they partially overlap due to a) the commissioning of scientific capabilities of the observatory without having fully assembled and integrated all antennas for overlap between the AIV and CSV processes, and b) the possibility of offering observing time to astronomers with only twelve integrated antennas that were scientifically tested, for the overlap between the CSV and Operation phases.

Figure 1: Construction and Operation Phases at ALMA



3.2. Data

A considerable amount of data has been generated in the last 30 years regarding the construction of the ALMA telescope, due, in part, to the collaborative nature of the ALMA project. In fact, the ALMA telescope is a one-of-a-kind venture where different institutions from the United States, Europe, and Asia participate. As I described earlier, I rely upon primary data obtained from two main sources. First, I collected information from interviews with scientists, engineers, and managers involved directly in the design, construction, and operation of the telescope array. Second, I use online archival data obtained from knowledge management software used by the ALMA organization and its partners. Following, I describe in detail the qualitative and quantitative data used in my dissertation.

3.2.1. Qualitative Data

I interviewed 43 astronomers, engineers and managers who participated in different stages of the development of ALMA. The interviews had an average length of forty-five minutes. The sample of interviewees is composed of professionals with a variety of knowledge specializations, including astrophysics, instrumental astronomy, computing/informatics, optics, mechanical and electrical engineering, and others. The interviews were conducted in an open-ended format to allow the respondents to describe, in their own words, their experience working in ALMA, how scientists and engineers solve the different problems faced at ALMA, and their participation in a Big Science Project that has moved through various phases of development, construction, and operation and that required working with people from different professional backgrounds and cultures.

Rather than collecting the entire set of data in one specific period and location, I alternated between data collection and data analysis. I held most interviews at three different times and locations. First, in July of 2014, I attended to the Astronomical Telescopes + Instrumentation Conference in Montreal, Canada, where I could make field observations of astronomers and engineers involved in the development and construction of complex scientific instruments in the field of radio astronomy, along with interviewing key people involved in the construction of ALMA, including Pierre Cox, the ALMA Director. Overall, in this conference I interviewed nine people involved in the development and construction of this scientific instrument. The main goal of the interviews and observations - in my first direct interaction with ALMA's contributors - was to acquire a better understanding of the most important characteristics of this scientific instrument and learn about how people from different professional backgrounds collaborate effectively in this Big Science Project through different phases.

Second, in May of 2015, I visited the ALMA headquarters and the Operations Support Facility located, respectively, in Santiago and San Pedro de Atacama, Chile. I was in both locations for ten days. During this time lapse, I interviewed twentieth people working at ALMA and participated in group meetings where engineers and scientists discussed the problems they needed to address in order to move forward with the scientific and technical tasks scheduled at ALMA. Furthermore, I had the opportunity of being in the offices and rooms where astronomers and engineers worked. By doing so, I could look at how people working at ALMA performed their activities and how they interacted with each other. Because I had a general understanding about ALMA, the main goal of these interviews and fieldwork was to learn more about the specific themes related to the construction of the instrument. Specifically, I was interested in the following topics: the different mechanisms used by scientists and engineers to collaborate effectively, the type of problems they needed to address, the different contexts where the collaborations occurred and the relationship between communities of knowledge, collaboration mechanisms and organizational contexts.

Third, in February of 2016, I visited the National Radio Astronomy Observatory (NRAO) in Charlottesville, Virginia. It is important to note that I was given permission to use the software management system related to the problem-solving episodes occurring in the construction at ALMA[1]. Due to this, the ten interviews I conducted were mainly focused on understanding how the software management system worked for scientists and engineers at ALMA, its most important characteristics and how the collaboration mechanisms used for problem solving episodes in different phases at ALMA could be reflected in the quantitative data contained in the software system.

Finally, during 2016 I made several online interviews to people that I had interviewed in one of my three field-works to ask them about the results I obtained from the quantitative data. In doing so, I could contrast the results obtained from statistical estimations with the perspective from individuals involved in these situations.

Below is a list of the 43 ALMA employees interviewed, including astronomers, engineers and managers, who have contributed to the conception and construction of ALMA. Moreover, the date were the interview took places is included in the table:

[1] More detailed information about the quantitative data is offered in the following sub-section.

Table 1: List of Interviews Conducted period 2014-2016

	Name	Role	Interview Date
1	Pierre Cox	Director	2014/2015
2	Monica Rubio	Board Director	2014/2015
3	Shinichiro Asayama	NAOJ Astronomer	2014
4	Bernhard López	Engineering Service Group Manager	2014/2015/2016
5	Vincent Hardy	Manager	2014
6	Simon Craig	System Engineer	2014
7	Mark Warner	Project Manager	2014
8	Kazuharu Yoshizawa	Product Manager	2014
9	Alejandra Voigt	Executive Officer	2015/2016
10	Alejandro Sáez	Correlator Engineer	2015
11	Shunsuke Sakai	Product Manager	2014
12	Hiroyuki Minamikawa	Product Manager	2014
13	Nick Whyborn	Array Lead Engineer	2015
14	Giorgio Siringo	Front-End Technical Lead	2015
15	Dan Spada	Chief Astronomer	2015
16	Ignacio Toledo	Data Analist, Astronomer	2015
17	Giorgio Fillipo	ESO IT Engineer	2015
18	Massimiliano Marchesi	ESO Antenna Project Engineer	2015
19	Cristián López	Astronomer	2015
20	Sergio Otarola	Electronic Technician	2015
21	Jaime Guarda	Front End Team Leader	2015
22	Silvie Vaucler	Astronomer	2015
23	Kenichi Tatematsu	NAOJ Scientist Manager	2015
24	Armin Silber	Front-End Engineer	2015
25	Rafael Mena	Human Resources Manager	2015
26	Victor López	Mechanical Engineering Group	2015
27	Octavio Hernández	Operation and Maintenance Planner-Coordinator	2015
28	Vasco Cortéz	System Engineer	2015
29	Roland Olivos	Infraestructure Maintenance Group	2015
30	Stuart Corder	Deputy Director	2015
31	Jorge Ibsen	Head of the Department of Computing	2015/2016
32	Andrew Baker	Astronomer	2015/2016
33	José Puga	AIV Engineer	2016
34	Max Simmons	Computing Engineer	2016
35	Allison Peck	Deputy Project Scientist	2016
36	Paul Vanden Bout	Former Alma and NRA Director	2016
37	Tony Beasley	NRAO Director	2016
38	Robert Dickman	Head New Initiatives Office, NRAO	2016
39	Ellen Bouton	NRAO Chief Archivist	2016
40	Tony Remijan	Program Scientist	2016
41	Catherine Vlahakis	Comissioning Scientist	2016
42	Phil Jewel	NRAO Deputy Director	2016
43	Richard Simon	Project Planning	2016

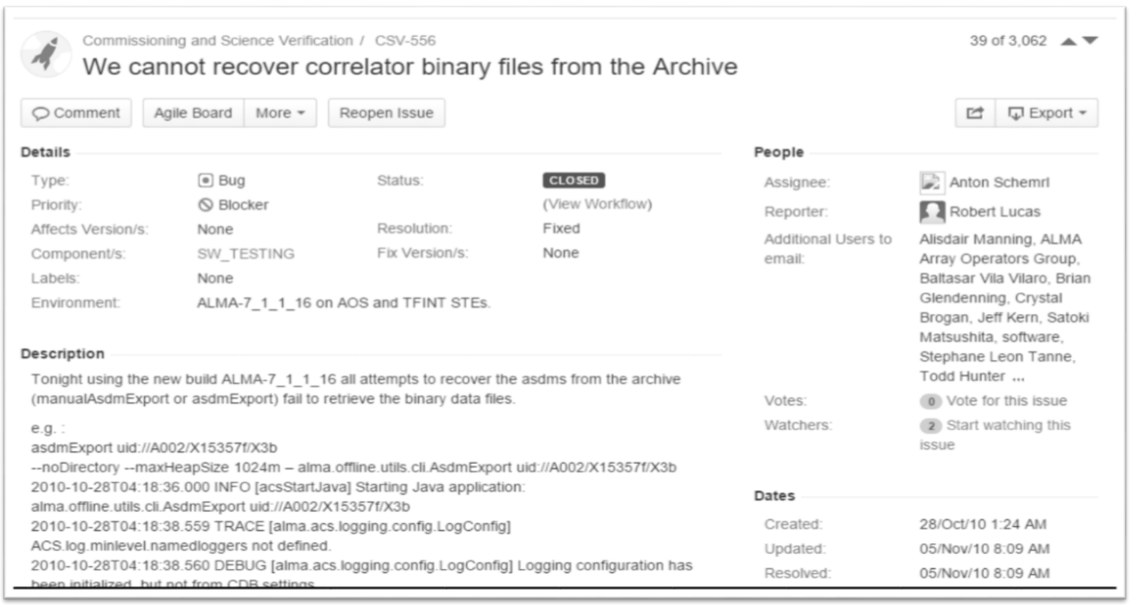
3.2.2. Quantitative Data

To test the propositions stated in Chapter 2, I constructed a dataset from two main sources. First, I collected data on organizational collaboration problem-solving activities from the knowledge-management system software used by the ALMA organization. A knowledge management system (KMS) refers to "a class of information system applied to managing organizational knowledge. They are IT-based systems developed to support and enhance the organizational processes of knowledge creation, storage/retrieval, travel and application" (Alavi and Leidner, 2001; p. 9). ALMA organization uses a proprietary knowledge-management platform software called JIRA, which was commercialized by Atlassian Inc. JIRA is used for project management, helpdesk services, and issue/problem tracking. Users of this knowledge software platform include NASA, Audi, Twitter, Amgen and the Department of Defense of the United States (Atlassian, 2016).

The engineers and scientists at ALMA started using this IT-based system in 2006. Since then, different groups and teams have created more than 80 projects focused on different milestones that had to be achieved for each telescope subsystem during both the construction and operation stages of the observatory array. More than 1,400 contributors of the ALMA organization, the main partners (NRAO, ESO and NAOJ), and other scientific institutions and private firms have participated in at least one of the projects originated on JIRA in the last ten years.

Within the data collected from JIRA, I propose to focus on two of the main projects developed in ALMA: The Assemble, Integration and Verification (AIV) project, and the Commissioning Science Verification (CSV) project. These two projects contain information from 2010 to 2014 on the activities and problems faced by the organization and their multiple partners and associates during the construction of ALMA telescope and during the process of testing the cutting-edge scientific capabilities prior to offering those capabilities to the astronomy community. Both projects in the JIRA system included activities that needed to be performed as well as problems that emerged during the construction and testing processes.

Figure 2: Example of a Problem Posted in the JIRA System



Specifically, I use the issues reported during the AIV and CSV processes. The JIRA system for the AIV process has stored 1,654 problems, from 2012 to 2013 (although activities in the AIV initiative began in 2008, problems only started to be separately tracked from tasks in 2012) and 1,384 for the CSV, encompassing a period from 2010 to 2014; accounting for 3,038 problems and 408 individuals participating in their solution.

Knowledge sharing activities within the JIRA platform allowed ALMA engineers and astronomers to solve problems arising in the AIV and CSV stages, by both informing relevant individuals within ALMA as well as providing a platform to engage external individuals. For instance, it was possible to add individuals who had participated in the design of a particular device by contacting them at their present workplace and allowing them access to the problem's information and to help in the solution. As shown in Figure 2, each problem registered on the JIRA system shows information about each problem's context, either in the AIV or CSV phase. This information includes: problem description, components involved, reporting date of the problem, resolution date, reason for the resolution: whether it was fixed, not fixed, duplicated, unable to fix; person reporting the problem and person assigned to solve it, priority level assigned to the problem; who contributed to the solution through comments; quantity of comments per contributor and how many people followed the problem solving process at JIRA, among other information of potential interest. Second, information about the problem-solving contributors from the JIRA database, such as individual affiliation and to which project and telescope subsystem the person belongs. I consolidated the data from these two sources to complete the information about the contributor's characteristics and merge that data with the JIRA.

Finally, since the focus of this study is boundary-spanning mechanisms, problem solving episodes and diverse contexts, I use the comments posted by the people from the ALMA organization in the JIRA system from a qualitative point of view, in order to have a more comprehensive understanding of the problem solving process developed by contributors at the ALMA project.

3.3.Summary

This research setting is particularly useful for my dissertation purposes for multiple reasons. First, the advantage of using the ALMA Telescope Array construction to test my propositions regarding boundary spanning mechanisms and problem solving episodes is that thousands of problems emerged during the development of this scientific instrument and people from different communities of knowledge had to collaborate to move forward with this initiative. Due to the importance of this project for different funding and research institutions from three continents, along with the need to coordinate hundreds of people working all over the world, a knowledge management system was required to track all the problems and activities during the construction an operation at ALMA. This information presents rich insights of the problem solving process developed by scientists and engineers, and what mechanisms were ultimately related to the effective solution of different problems occurring during the construction of this Big Science Project.

Second, a critical characteristic of the data collected at ALMA is that it offers two different contexts, one scientific and the other engineering, which are partially overlapped. This research setting minimizes the heterogeneity that could arise by using two different organizations, each one with its own particular context. By employing the assembly, integration and verification (AIV) and the commissioning science verification (CSV) context, I studied the influence of boundary spanning mechanisms on problem solving effectiveness and their relative significance in scientific and engineering contexts in a research setting where both contexts received the same impacts from both outside ALMA organization and within the boundaries of the initiative. For instance, as described in the next chapter, when the operation phase was beginning with its activities, there were pressures in terms of resource constraints to both the AIV and CSV phase, both financially and time wise.

Overall, in this dissertation I propose that there are specific boundary spanning mechanisms that are capable of bridging different barriers that emerge in the of problem solving process during the development of large innovation initiatives. Along with that, I argue that these spanning mechanisms will differently influence problem solving effectiveness depending on the context where the problem was discovered and the solution process takes place. In the following chapter, I present descriptive statistics and qualitative results that provide a better understanding of the most relevant elements of the ALMA organization, which provides a clearer picture about the development and implementation of this Big Science Project.

Chapter 4. Descriptive Results

Before testing the predictions proposed in Chapter 2, using the dataset of problem solving episodes at ALMA, I describe the ALMA Telescope Array's most important dimensions based on the data gathered from the qualitative portion of my dissertation, which are strengthened by descriptive statistical results and quotes obtained from ALMA's software management system.

The dimensions I analyze in the following subsections are: ALMA as a complex system, problem solving episodes, organizational contexts and collaboration mechanisms.

4.1. ALMA as a Complex System

A complex system is characterized by a large number of components that are highly interrelated (Gavetti and Levinthal, 2000). In the case of ALMA, since the beginning of the negotiations between the different partners in the late 1990's, it was clear that the challenges of designing and building the largest radio telescope ever would be a complex task. As ALMA's first director - Paul Vanden Bout remembered, "[W]e knew that it would be a very difficult enterprise to merge three different telescope designs that included five subsystems, partially resulting from different scientific specifications made by distinct astronomy communities" (personal interview, 2016). The participation of individuals with different cultural and scientific backgrounds, who were all dedicated to creating and transferring knowledge from different types of technologies, makes ALMA a good example of a complex organization.

Moreover, ALMA stands out in how both scientists and engineers interacted with each other when compared to other astronomical initiatives. For example, according to

Daniel Espada, an ALMA astronomer, “In my previous job as an astronomer, I worked with engineers, but it was different; you could touch the instrument, because you had to operate it and get information from it. Here, it is very different, it is like a big firm where we have to coordinate with hundreds of people” (personal interview, 2015). Giorgio Siringo, the Front End Engineer Leader, agreed, “I worked with only five other astronomer scientists in my last job… here in ALMA you have to engage in massive interactions with other people” (personal interview, 2015). In other words, organizational complexity at ALMA increased not only due to the inherent complex technologies embedded in the development of the instrument, but also because of the magnitude of the ALMA initiative.

Meanwhile, and in contrast with other Big Science Projects, at ALMA, due to the need for employees to directly manipulate the array components of the telescope in a harsh environment - in terms of temperature, altitude, weather conditions and relative isolation from urban communities - scientists and engineers faced problems in conditions with limited control over external variables. Armin Silber, pondered upon the differences: “Because employees in ALMA that work above 5,000 meters of altitude need to interact closely with different devices from the varied observatory sub-systems, the role of human beings cannot be compared with the optical telescopes built by NASA, where once the telescope is in orbit, human intervention is much less” (personal interview, 2015). The combination of the development of innovative technologies with the execution of ordinary tasks resembling operational activities performed in productive industries, like mining, was common at ALMA.

For instance, different array configurations were required to run the different research projects awarded with astronomical time at ALMA. That meant that the antennas had to be specifically positioned in the plateau to adjust to certain scientific requirements. To accomplish this task, two trucks driven by professionals and especially manufactured for this goal were used to move the antennas from one place to another within the array site. The relationship between the development of cutting-edge technologies of ALMA artifacts along with daily activities offered an intriguing picture of the development of Big Science Projects, in the sense that producing breaking science was not just about creating new technologies and innovative instruments, but also about implementing operational activities that were unrelated to producing these technologies. Consequently, when contributors at ALMA faced diverse problems, they needed to consider that the source of the problem could either have been a high-level technological issue, a human activity, or the result of environmental shocks.

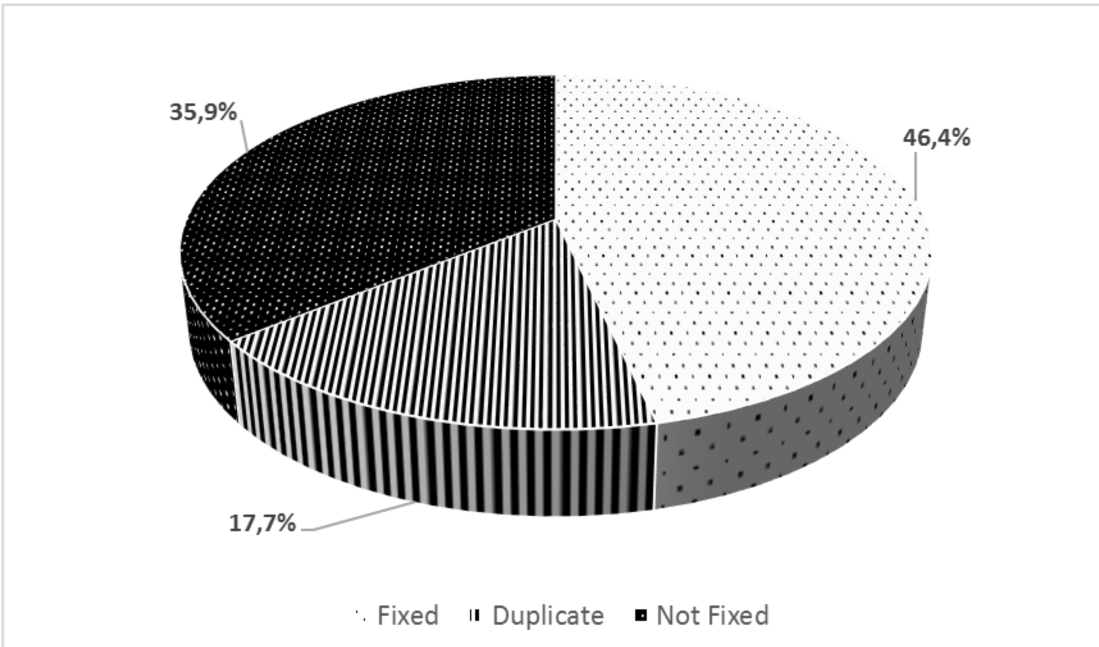
Overall, ALMA has a highly complex system, and to acknowledge that this complexity is not only due to the different technologies and heterogeneity of the participants, regarding nationalities and professional communities, but to many different factors, allows me to focus with a better understanding on the elements in question, namely, problem-solving activities, collaboration mechanisms and different organizational contexts.

4.2. Problem Solving Activities

4.2.1. Problem Characteristics in AIV and CSV phases

As mentioned in Chapter 3 of this dissertation, two critical phases took place from 2008 to 2014, during the construction of the ALMA Telescope Array: the assembly, integration and verification phase (AIV) and the commissioning and science verification phase (CSV). Based on the information collected from the JIRA software system, 3,038 problems were faced during these phases. However, only a portion of these problems could be solved. Figure 3 provides a breakdown of the three possible results once a problem was reported in this knowledge management system.

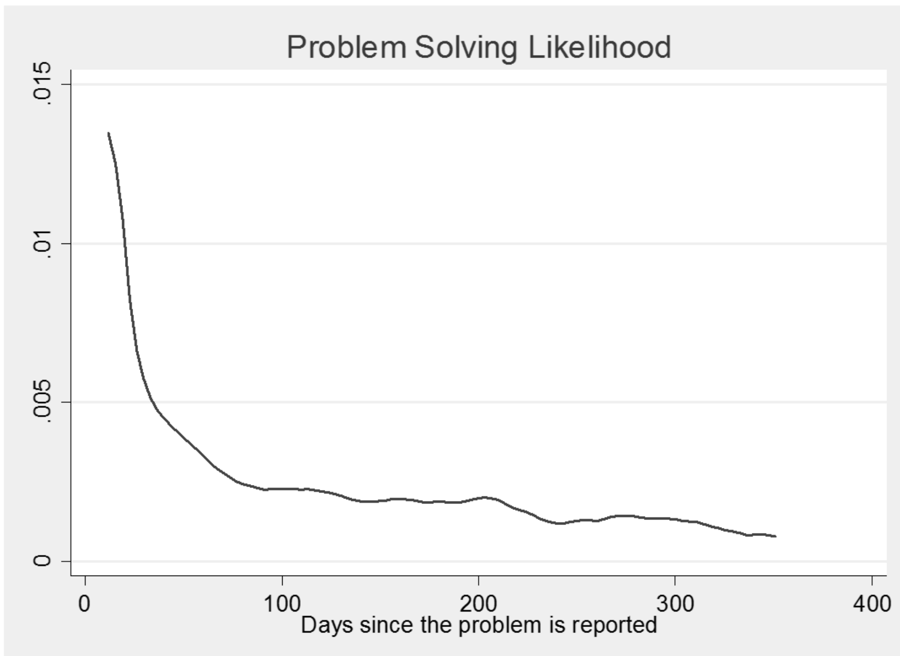
Figure 3: Problems Outcomes in CSV and AIV Phases



As shown in figure 3, 46.4% of the problems were solved by the ALMA community, while 35.9% were not. Moreover, 17.7% of the problems reported in the system were tagged as duplicates. This means that either the problem had already been solved or it was being solved at that moment under another problem. The high percentage of duplicates is explained by many factors: first, the size of the ALMA initiative could prevent ALMA's contributors from being fully aware of all the activities being performed within the organization. Second, since the work was organized in shifts and many contributors only participated for a limited time span, people could have missed many problem episodes during the construction of ALMA.

Regarding the likelihood of solving a problem on these two phases, figure 4 shows that the highest chances to solve a problem were the first days after the problem was reported. After that, the likelihood of solving the problem decreased abruptly in the next 60 days. After that, the chances of fixing the problem reduces, but at moderate rates

Figure 4: Problem-Solving Likelihood in CSV and AIV Phases



4.2.2. Problem Solving Process

Within the problem-solving process, it is possible to differentiate the process of finding and defining the problem from the process of elaborating and testing courses of actions to solve the problem. The JIRA online problem repositories allowed identifying the end of a process and beginning of another, as one of the engineers expressed in one comment written in the online system: “Jesus, those three glitches and those 3 TE error look perfectly correlated. That’s the problem. This is the first time we notice this correlation and I think it's convincing. How do we proceed?” Sometimes, it was necessary for the solver to emphasize the problem and to be sure that the possible solutions have direct relationship with it. Alejandro, an engineer with responsibilities in the correlator commented in the problem forum: “It seems like this discussion has been dragged to other focus. The main problem is the presence of a huge DC component (high amplitude in 0Hz channel) in some sub-scans”. In these cases, making problem finder responsible for finding a solution was useful because the flow of information between problem formulation and problem solving spaces could flow easily.

From the interviews I conducted with ALMA’s contributors, it was clear that when a problem was reported by either an engineer or an astronomer, regularly the problem reporter did not know the real level of problem complexity. As an astronomer involved in the integration of the antennas and the verification of the scientific capabilities at ALMA noted, “People only realized a problem was complex once they started working on it” (personal interview, 2016). One implication of this fact was that the problem solver could not develop potential solution searches after being informed of the problem. Furthermore, from the comments written in the problem solving online platform, it seems that the problems faced by ALMA’s contributors were not static and evolved overtime. For example, John - an astronomer – commented in the problem forum: “Bill… this problem morphed into an inability to calculate scaling factors causing a failure to calibrate the correlator….” Another engineer, Michael, also metaphorically stated that the source of the problem was not static and difficult to isolate: “Pablo: obviously, every-time there is a recorded occurrence it means the logging script is not running... we are chasing a tricky mouse here!!!”

In these situations, where complexity cannot always to be assured by the problem finder and it appears that problems are not stable, being able to have connections between problem finding-formulation and problem solving spaces was key for problem-solving effectiveness during the construction of the ALMA Telescope array.

Finally, since individuals could not always assert the difficulty of a problem prior to engaging in a solution search, measuring its complexity according the number of components involved was not always useful. Instead, the complexity in problem solving episodes should also be identified through endogenous indicators focusing on the degree of difficulty in finding a solution to a specific problem. Likewise, ALMA's engineers and astronomers shed light on a different way to measure endogenous problem complexity: their motivation to be informed about the progress of a solution. A former Commissioning Scientist Verification (CSV) team leader highlighted, "I was very interested in the type of problems that challenged me, in that it was very puzzling to find a solution to them" (personal interview, 2015). Similarly, Catherine Vlahakis, a NRAO astronomer, noted "[W]hen a difficult problem emerged, it was clear that more and more people started to look at it and began to follow it up in the JIRA system" (JIRA is the knowledge platform system used by ALMA to track problems in the execution of the activities in the observatory) (personal interview, 2016).

Thus, based on the information collected from the JIRA system, one potential alternative to measure endogenous problem complexity is to include a measure on how interesting the focal problem was. Specifically, the JIRA dataset allows counting the number of individuals interested in learning more about the problem, by measuring the number of people who followed it using the "watchers" option in the system. By doing that, they did not necessarily have to contribute to the solution by commenting in the forum, which allows detangling the interest level from the relative effort involved in the focal problem.

4.3. Organizational Contexts

The interviews conducted in the last three years hint that professionals at ALMA faced different constraints depending on their work context. Specifically, I have identified three unique organizational contexts that reflect special features where ALMA astronomers and engineers worked. The first two correspond to the period between the 2008 and 2014, when the ALMA organization focused on two sequential but at the same time partially overlapping construction phases: The Assembly, Integration and Verification project (AIV) and the Commissioning Scientific Verification project (CSV). The third is the operation phase, which began its activities in 2012.

In the AIV context, efforts were concentrated on promptly completing the assembly and technical verification of the array. For example, as one of the array group engineers recalled, “In the AIV project, we were only focused on integrating the 66 antennas” (personal interview, 2014). This ends-based orientation for the AIV process had direct implications on the management of problems that arose in this environment. Bernhard Lopez, ALMA system engineer, noted “[W]e prioritized spending time on the problems that directly affected the proper development of activities required to complete our schedule in the AIV project; if we found a problem but it did not strongly limit our progress, there were not many incentives to solve it” (personal interview, 2016).

In contrast, during the commissioning science and verification (CSV) environment, problem solving activities were not only encouraged, due to the practical implications for the correct development of the process overall, but CSV team leaders were also interested in creating opportunities for the individuals working on them to engage in discussions about the nature of the problems faced in this process. Alison Peck, former CSV manager, remembered, “In the earlier cycles of the CSV phase, it was common and highly advisable to spend more time after our daily meetings to talk about the multiple problems faced those days” (personal interview, 2016). Likewise, the CSV phase reflected an increase in the scientists and engineers’ motivations to explore different aspects of the ALMA project in comparison to the AIV phase. One of the astronomers that participated in the CSV environment said why, “The science commissioning project was the cutting-edge part of the telescope where many of the brightest radio astronomers in the world participated. That is the most interesting phase in ALMA” (personal interview, 2015). Overall, the CSV project can be considered as a more scientific-driven context than the AIV project.

Despite the differences between these two contexts, it is important to note that these two processes ran concurrently from 2010 to 2013. Moreover, since nearly all the astronomers working at ALMA were hired for the CSV process and engineers came from the AIV project, professionals moved continuously from one environment to the other since the expertise of both astronomers and engineers was necessary for many of the activities and related problem solving episodes. An ALMA astronomer recalled, “I was working the night shift when AIV and CSV activities were both in full swing, so some nights I would do AIV work and other nights I would do CSV work” (personal interview, 2015). Thus, the engineering and scientific contexts represented by the AIV and the CSV projects involved both engineers and scientists, with their own motivations, values and tacit norms, as previously highlighted.

I previously defined contributors that have been involved in more than one phase in a Big Science Project as phase spanner. As an example of the differences in the proportion of boundary spanners between the scientific and the engineering phase, Figure 5 exhibits the problem network for both contexts in 2012, in which the blue nodes reflect the individuals that participated in both phases, while the red nodes represent individuals that only participated in one of the phases. The graphs show a clear predominance of involvement of people from the engineering context in the scientific phase. Instead, in the engineering phase, individuals that specialized on problems reported in this context almost matched the boundary spanners. In addition, many of the non-boundary spanners in the engineering phase were more central in the problem network.

Figure 5a: People Involved in Problem Solving Episodes in Engineering Phase

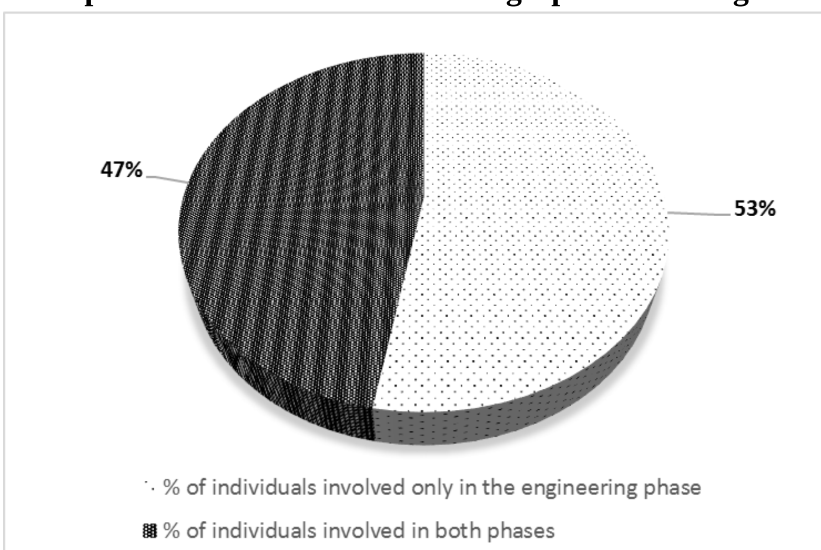
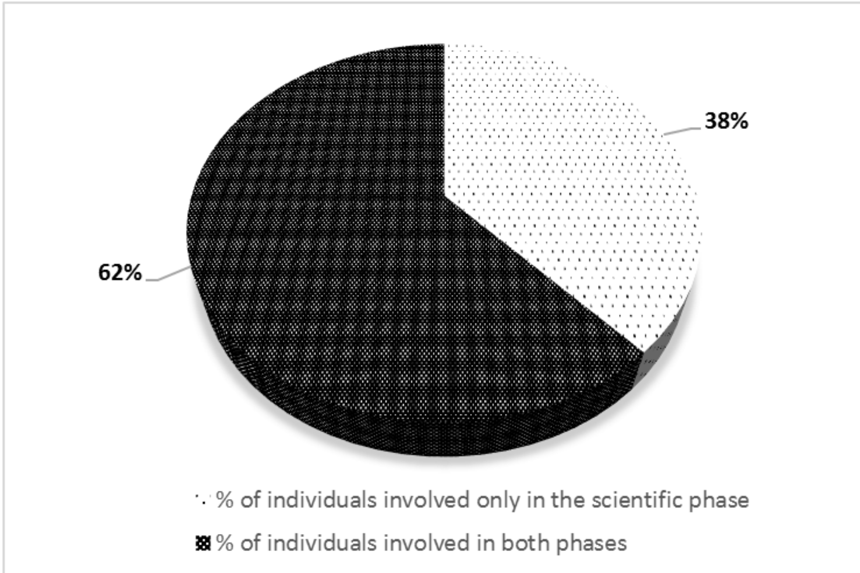


Figure 5a: People Involved in Problem Solving Episodes in Scientific Phase



The operation context reflected an entirely new context for the astronomers and engineers involved in ALMA. This final phase was focused on running the observatory for the selected astronomical projects. For instance, efficiency concerns became even more important than in previous stages. Bernhard Lopez stated, “Now, in the operation phase, we need people with general knowledge about the different aspects of ALMA. In the construction phase, we needed specialists able to deal with specific problems… That was necessary, but it was much more expensive” (personal interview, 2015). Moreover, the professionals participating in this stage were able to benefit from the advances achieved in the prior development and construction stages. As one of the engineering managers recalled, “In the operation stage, we have more knowledge about what works and what does not. We are focused on increasing efficiency” (personal interview, 2014).

However, the emphasis on efficiency in the operation context not only impacted the activities developed in this environment, but also affected the commissioning and scientific verification context. As one of the CSV former team leaders highlighted, “The pressure for using the limited resources - especially time and human resources - was higher as we got closer to the operation phase" (personal interview, 2016). Thus, it can be said that the different organizational contexts identified in the construction and operation phases place specific constraints on the individuals who participated on other contexts at ALMA observatory. Using the data collected from the JIRA system, the correlation between the problem fixed variable and a time variable that measures when the problem was reported in the CSV context is of -0.1031. This implies that the closer this phase was to ending, the lower was the likelihood to solve the problem, which is aligned to the qualitative information regarding the increasing constraints faced by people at CSV once they were close to the operational phase. On the other hand, the same correlation for problems that emerged from the AIV contexts is equal to 0.0023. A possible explanation for the inexistent relationship between these two variables can be found in the workplace conditions established in the AIV process. Specifically, in this engineering type of environment, efficiency-driven practices were sponsored; therefore, pressures in terms of higher constraints of time and resources present at the beginning of the operational phase did not influence problem-solving effectiveness.

Figure 6 describes the priority for problems reported in the JIRA system in the CSV and AIV contexts. As shown below, the total percentage of high-priority problems in the CSV phase is significantly higher than in the AIV phase. When putting together the blocker, critical and major problems, in the scientific context, 36% of the problems were considered high priority, in contrast to only 10% for engineering context problems.

Figure 6: Problem Priority in CSV and AIV Phases

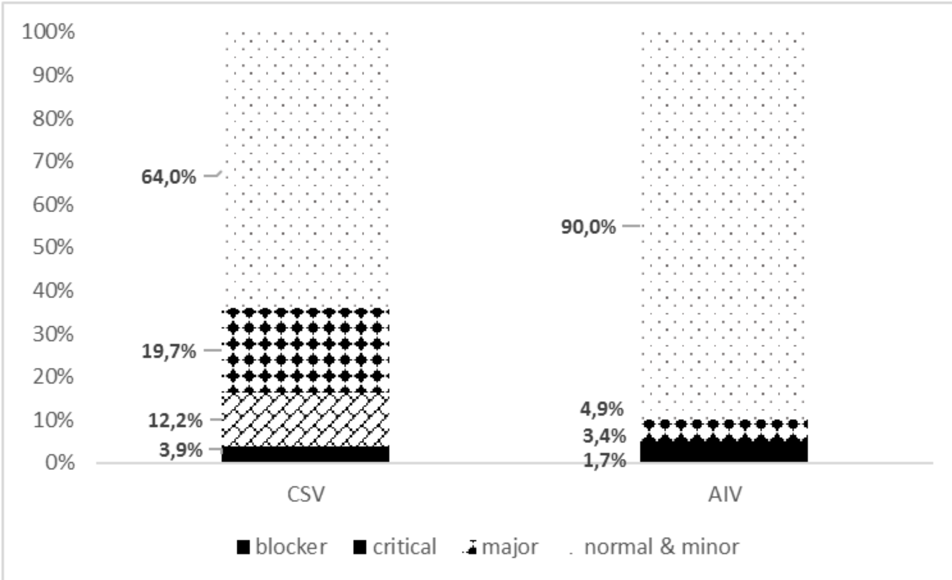
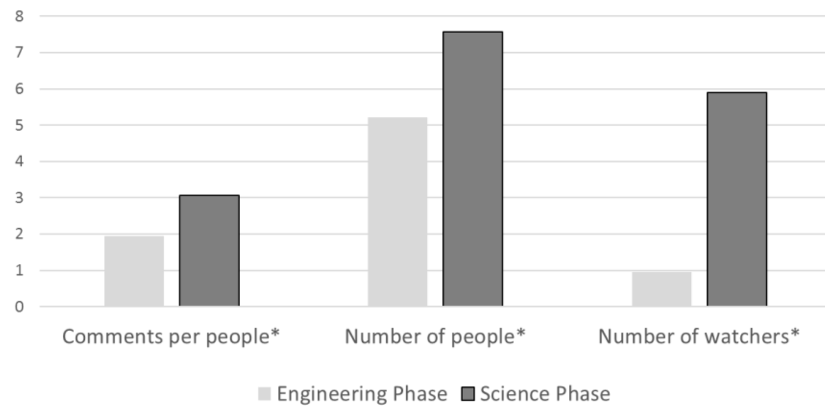


Figure 7 shows the differences in how scientists and engineers collaborate to solve problems in the commissioning science verification phase in comparison to the assembly, integration and verification phase. The graph shows that the average number of comments per person made in the science phase for high-priority problems significantly exceeds those made in the engineering phase (3.07 vs. 1.95). Similarly, the average of contributors for problems in the science phase is higher than the average of people involved in engineering phase problems (7.57 vs. 5.21). These results reflect that higher efforts are concentrated on dealing with solving problems reported in the scientific phase versus the engineering phase.

Figure 7: Scientific Phase vs. Engineering Phase on High Priority Problem Solving Episodes



* Significant at p<0.001

As mentioned before, the JIRA platform allows examining how many people on each phase were interested in following the development of the problem-solving episode without necessarily contributing to its solution. The graph shows that, in the science phase, the average number of watchers for high priority problems was considerably higher compared to the watchers in the engineering phase (5.89 vs. 0.96). This likely reflects that the level of interest to understand and learn more about the problems emerging from the construction of ALMA were stronger in the scientific phase of this initiative.

The CSV problem online database allows verifying that people involved in problem solving episodes in the scientific environment were not only focused on fixing the problem, but had the time and freedom to understand and learn from them. As one of the science leaders in the CSV phase commented in the problem forum, highlighting the importance of studying the focal problem: “Yeah!! Congratulations to Jeff, Tsuyoshi, Denis and all those who worked hard to document and study this problem”. Another engineer in the CSV context still needed to have more information about the problem once it had been solved: “Eric, can you explain how this was fixed and resolved. I can't seem to see what happened on the ticket”. Sometimes the problem episode for solvers in the CSV context is something more than just an activity to fix a situation that does not allow the activities to move forward, but it also is related to a challenge that needs to be solved. For instance, Allison Peck commented this about a problem that was successfully solved: “Thanks for solving that mystery, David. We don't usually use this parameter, we just try not to leave anything in "0", in case some value is needed, so we can change this easily, and we'll warn people to use "h" even if it's a nonsense number”.

Another source of heterogeneity between the CSV and AIV process is related to the type of individuals involved in problem solving, regarding their institutional affiliation. As shown in Tables 2 and 3, there is clearly a lower percentage of CSV problems that were discovered by ALMA employees compared to AIV problems (67.9% vs. 79.7%). The same occurred regarding who was responsible for fixing the problem (82.6% vs. 88.9%).

Table 2: Problem Finder vs. Problem Solver Affiliation in CSV Phase

Finder/Solver	ALMA	NRAO	ESO	NAOJ	Other	Total
ALMA	57.1%	11.4%	4.6%	1.7%	7.8%	**82.6%**
NRAO	2.8%	1.3%	0.2%	0.1%	0.4%	**4.8%**
ESO	4.3%	0.9%	0.8%	0.0%	0.3%	**6.3%**
NAOJ	0.7%	0.1%	0.1%	0.1%	0.1%	**1.1%**
Other	3.0%	1.4%	0.1%	0.0%	0.7%	**5.2%**
Total	**67.9%**	**15.2%**	**5.8%**	**1.9%**	**9.2%**	**100.0%**

Table 3: Problem Finder vs. Problem Solver Affiliation in AIV Phase

Finder/Solver	ALMA	NRAO	ESO	NAOJ	Other	Total
ALMA	71.5%	7.1%	5.2%	2.9%	2.3%	**88.9%**
NRAO	1.1%	0.2%	0.0%	0.1%	0.1%	**1.5%**
ESO	0.8%	0.0%	0.1%	0.0%	0.1%	**1.0%**
NAOJ	0.2%	0.0%	0.0%	0.1%	0.0%	**0.3%**
Other	6.0%	0.8%	0.1%	0.2%	1.1%	**8.2%**
Total	**79.7%**	**8.1%**	**5.4%**	**3.2%**	**3.6%**	**100.0%**

The reason why a greater percentage of AIV problems is found and solved by ALMA employees compared to CSV problems can be explained by the following quote from an Astronomer engaged in both types of contexts: “you need a higher level of expertise for CSV problems than AIV problems, and this expertise is more globally distributed” (personal interview, 2015).

4.4. Collaboration Mechanisms

As noted earlier, in order to achieve the scientific and technological goals at ALMA, individuals from different educational backgrounds, work experiences, and cultures had to collaborate successfully. At the beginning of the construction of ALMA, the differences between astronomers and engineers made it difficult to advance in the scheduled activities and to solve the problems that emerged. As an ALMA electrical engineer remembered, “In the first months of working with scientists, it was hard to fully understand what they wanted from us” (personal interview, 2015). As aforementioned, when communication problems exist between different communities, they can be called “trading zones” (Galison, 1997). People at ALMA used multiple collaboration mechanisms to overcome the challenges imposed by the trading zones.

First, creating communication channels between people working at ALMA was critical due to the nature of this initiative. As Nick Whyborn, Array Lead Engineer, argued, “The most important problem in a Big Science Project like ALMA is communication, since the magnitude of this type of initiative forced everybody to focus on their specific tasks” (personal interview, 2015). Both informal and formal meetings were complemented by the use of the JIRA online knowledge platform system that allowed ALMA to organize the different projects needed to build and operate the array. Regarding face-to-face meetings, “science meetings” were held at the OSF in northern Chile, every day at 8:15 AM, where astronomers communicated their needs to the engineers in terms of the telescope and the problems with the instrument. Moreover, “engineering meetings” were held daily at 5:00 pm, where engineers addressed how they responded to the astronomers’ requirements.

The online platform system tracked all the activities and problems faced by the different teams at ALMA, facilitating the collaboration of engineers and astronomers that were not working in the ALMA operation facilities. As one of the AIV engineers pointed out, “The IT knowledge software platform used to track the activities and problems was key to coordinate different individuals that live far from Chile” (personal interview, 2015). Coincidentally, Alison Peck recalled, “If we had a problem we could upload it [to the online system] so the device designers could respond questions and see the information related to the problem, no matter where they lived [in]” (personal interview, 2016). Thus, it seems that the JIRA system made the creation and transfer of knowledge more efficient, and also opened up the knowledge network by including both individuals that worked for private contractors and for the associate partners of the observatory in Asia, the United States, and Europe, such as NAOJ, the NRAO, and ESO, respectively.

The adoption of the online proprietary platform to facilitate the coordination between different members of ALMA was not easily accepted by some, who were not used to employing this type of collaborative tools. A CSV manager remembered, “At the beginning, I thought that using software to track the activities and problems was going to be troublesome. Now, I think we couldn't have done what we accomplished without JIRA” (personal interview, 2016). Throughout the interviews conducted with different professionals at ALMA, it was mentioned that, along with the multiple advantages of using this platform, one of the key success factors for the adoption of the JIRA system was the fact that the online platform was easy to use. Finally, in addition to the aforementioned benefits of using the JIRA software, the online tool allowed the ALMA organization to create a knowledge repository that tracked how activities and problems have been solved in the past.

Second, for effective communication, people needed to understand what they heard from their counterpart. To do this, individuals had to invest time to learn more about other technical languages. Alejandro Saez, for example, remembered, “We [engineers] began to know more about their [scientist’s] language and they learned about our language” (personal interview, 2015). Similarly, Tony Remijan, a former CSV Team Leader Astronomer recalled, “When I arrived at the site, I attended engineering and computing meetings to learn more about their language” (personal interview, 2016). Thus, efforts to improve understanding between the different communities were developed by individuals that found the problems; as Tony Remijan observed, “We had to carefully explain to the engineers the importance of having the appropriate resolution, because they didn’t know the implications for science” (personal interview, 2016). In addition, astronomers and engineers used the same software to work with data, which helped merge the two languages used by ALMA employees. As an AIV former engineer recalled, “Using the same software forces you to use the same words” (personal interview, 2015). In summary, one of the primary collaboration mechanisms at ALMA was the ability for different people to understand the “language” used by other professionals. At the same time, because astronomers and engineers used the same tools and devices and had frequent conversations, it seems that a new sub-language emerged over time.

Problem solvers had to use different mechanisms to effectively create and transfer knowledge to fix the problems during problem-solving episodes. This flexibility of using multiple collaborative instances could be seen in different forms, such as asking for help to individuals in a high hierarchy level: “In some cases, when we did not know how to solve a problem, after a couple of days we asked for help from our team leader,” a mechanical engineer commented (personal interview, 2015). Others reached out to experienced astronomers to guide them in the solution search: “When a problem was reported, astronomers gave us clues”, said a correlator engineer (personal interview, 2015). Moreover, problem solvers had the chance to impose higher order strategies to address specific problems, such as selecting a group of people to focus on a major obstacle: “Many times if the problem was not solved in a couple of weeks, we created a task force to deal with it,” noted a Deputy Project Scientist (personal interview, 2016).

Third, people help bridge knowledge barriers between different contexts by spanning boundaries. As one array Engineering Leader said: “My astronomy background has allowed me to know what astronomers want”. Another astronomer noted “…in my previous position as an astronomer, I worked with engineers but it was different, I could touch the instrument, because I had to operate it and get information from it, but here, my former experience has been useful to understand engineers,” or as Alison Peck, former CSV team leader said in an interview in 2016: “I’m a point of contact between the engineering and the scientist team”.

Likewise, when solving problems in a specific context, regardless if it is in the CSV or AIV phases, people from the other contexts were assigned to fix the problems due their capacity of bridging different streams of knowledge in the cross phase. For example, this problem discussed in the CSV context was assigned to someone who has a good knowledge about people working in the AIV phase: “I think the next step in resolving this is to understand what caused the TE Errors in the correlator. Assigned to Nick, as I'm not sure who in AIV is the right place to start”. Similarly, an AIV engineer commented “these are correlated with the Timing Event errors so it would be unexpected for them to go away, but we should have the data now so we could look and see if we still have a problem or not. Perhaps someone on CSV could have a look”.

Finally, astronomers and engineers used different tangible tools such as graphs, images, and software coding outputs to communicate the problems they faced at ALMA throughout the online management system. According to the insights provided by the people engaged in the construction and operation of the array, these tools were employed in two phases of the problem solving episodes. First, some of them were used when there was a problem to report and it was necessary to share any information that could help in the solution, including to those who did not have the same professional background. Second, people contributing to the solution of a specific problem used graphs, images, and software coding outputs to notify the progress made in both identifying the problem’s source and progressing towards finding a resolution.

One interesting aspect about using artifacts as communication bridges is that their usefulness to permeate professional boundaries has changed over time. It seems that these tangible objects have the potential to mutate from being a mechanism that blocks collaboration to one that eases communication between the different communities of knowledge. As Miguel Guarda - an ALMA mechanical engineer - recalled, “At the beginning of the AIV effort, the astronomers sent us graphs saying: ‘here is the problem’, and we did not understand how to interpret the graphs; however, after a couple of months, those graphs helped us to solve the problems with the scientists" (personal interview, 2015).

4.5. Summary

There is a large variation in problem solving activities at ALMA. The descriptive statistics, along with the responses of contributors at ALMA, show the main features of the problems that emerged at ALMA, the differences between problems and behaviors of people when they work in scientific and engineering contexts, and the different types of collaboration employed in these activities. The purpose of this dissertation is to examine which collaboration mechanisms - especially regarding boundary spanning - are more effective for solving problems in both science and engineering contexts.

Chapter 5: Results

In this chapter, I refine the propositions posited in chapter 2 by making specific hypotheses based on the ALMA context. Then, I test these hypotheses using the quantitative data collected from the knowledge-management software used by ALMA personnel to seek out and share knowledge to solve problems.

5.1. Hypotheses

Based on problem solving processes, boundary spanning, science, technology, and big science project literature, I suggested in Chapter 2 six propositions related the influence of different boundary spanning mechanisms on problem solving effectiveness and how these effects were contingent to the context of emergence of the problem. As described in Chapter 3, in the ALMA Telescope Array initiative, specific phases that resemble the scientific and engineering context were developed. Specifically, based on findings from the qualitative portion of this dissertation, it is possible to assert that the commissioning of the scientific verification phase (CSV) can be identified as a scientific context, whereas the assembly, integration and verification phase (AIV) can be conceived as the engineering phase.

Drawing on problem formulation and problem solving processes research, I posit that problem solvers able to bridge the formulation with solving information space will positively influence problem solving effectiveness. Moreover, I argue that in scientific contexts, problem finder-keepers will be more helpful in comparison to engineering contexts due to the lack of formal structures, procedures and rules that diminish the organizational tools available to allow the effective flow of information and knowledge from the problem formulation space to the problem-solving space. Applying these propositions to the ALMA Telescope Array case, I propose:

Hypothesis 1. Problem finder-keepers positively affect problem-solving episodes in both the CSV and AIV contexts.

Hypothesis 2. Problem finder-keepers influence problem solving in the CSV context more positively than in the AIV context.

Secondly, based on boundary spanning and big science project literature, I propose that scientific-engineering phase spanners are positively related to effective solution of problems in both scientific and engineering contexts. Moreover, I suggest that phase spanners are of higher value when a problem arises from the engineering context because in scientific contexts their organizational structure will be more disorganized and hierarchies are not so clear. For this, it will be more beneficial to have problem solvers who have had experience in the scientific side for problems emerging in the engineering context, so they can replace the absence of organizational tools needed to be efficient in identifying the required knowledge to solve the engineering context problem. Again, applying these propositions to the CSV and AIV context, I suggest the following hypotheses:

Hypothesis 3. CSV-AIV phase spanners positively affect problem-solving episodes in both the CSV and AIV contexts.

Hypothesis 4. CSV-AIV phase spanners influence problem solving episodes on AIV context more positively than in CSV context.

Third, resting on knowledge networks and science and technology literature, I pose that scientific context problem solvers with high levels of knowledge brokering in the engineering context are negatively related to problem solving effectiveness. In contrast, I propose that engineer context problem solvers with high levels of knowledge brokering in the scientific context are positively associated with problem solving effectiveness. Consequently, converting those propositions in hypotheses bases on the CSV and AIV context in the ALMA Telescope Array case, I hypothesize that:

> *Hypothesis 5.* AIV context knowledge brokers negatively affect problem-solving episodes in the CSV context.

> *Hypothesis 6.* CSV context knowledge brokers positively affect problem-solving episodes in AIV contexts.

5.4. Data and Methods

5.4.1. Sample

The hypotheses were tested using a unique, confidential dataset constructed from information provided by the Atacama Large Millimeter Array organization. I collected data from the knowledge-management system software used by ALMA, called JIRA[2]. I focused on two main stages developed in the ALMA pre-operation phase: The Assembly, Integration and Verification (AIV) stage, and the Commissioning Science Verification (CSV) stage, which can be viewed as an engineering and scientific phase, respectively. These two phases contain information from 2010 to 2014 on the activities performed by the organization and their multiple partners and associates during the construction and the process of testing the cutting-edge scientific capabilities prior to offering them to the

[2] A more detail description of the data can be found in Chapter 3.

astronomy community. Both phases were registered in the JIRA system, including tasks and problems that emerged during the AIV and CSV processes. Despite most of the information used to test the hypotheses came from the problem-solving reports, I also employed task-related information, provided by different ALMA contributors that posted on the knowledge management system software, in order to construct the network variables required to test my propositions, especially regarding the cross knowledge broker variable.

Although the sample size varies depending on the analysis, the following provides an overview of the construction of the base sample. The starting sample was constructed of 1,384 and 1,654 problem observations for the CSV and AIV stages, respectively, covering the period from 2010 to 2014; together, these account to 3,038 problems, containing 31,327 comments made by 408 individuals participating in the solution of these issues. 170 and 368 CSV and AIV problems were categorized as duplicate problems by ALMA contributors, meaning that those problems either had been solved or were being solved at that time by people at ALMA. This reduced the sample to 1,214 CSV and 1,286 AIV problems. After removing observations due to missing data, I obtained a sample including 846 and 1,059 observations for CSV and AIV, respectively.

5.4.2. Measures

Dependent Variables

Problem-Solving Effectiveness is a binary variable equal to 1 if the problem reported in the AIV and CSV stages was solved within one year since from its reporting date, and 0 otherwise. The reason to restrict the problem solution to a one-year time frame is based on interviews with AIV and CSV managers who stated that when the problem was open for longer, occasionally the issue was closed and some of them were tagged as a "solved". For this, they suggested limiting the time to one year.

Independent Variables

Problem Finder-Keeper is a binary variable equal to one if the individual that reported the problem in the JIRA system was the same individual who was assigned to solve the problem and 0 otherwise.

Phase Spanners is a binary variable equal to 1 if the problem solver contributed either to the solution of a problem or to the execution of tasks to both CSV and AIV stages in the year prior to the year in which the problem was reported, and 0 otherwise.

Cross-Context Knowledge Broker. Consistent with prior research on knowledge broker (e.g. Nerkar and Paruchuri, 2005), I used the problem solvers' structural hole network coefficient to account their knowledge broker capability. This variable is measured by constructing a network of problems and tasks contributors in moving one-year windows for the CSV and AIV phase, separately. A network of contributors was obtained by using all the tasks and problems reported in the one-year period prior to the problems' reporting year. The contributors who commented on the tasks and problems faced in the CSV and AIV processes were considered an affiliation network. Each task and problem has multiple contributors, and each contributor could participate in multiple activities. This affiliation network, which is a two-mode network of activity to contributor, was transformed into a contributor network, which is one-mode network of contributor-to-contributor, using UCINET VI (Borgatti, Everett and Freeman, 2002). This leads to a network of contributors with co-participation as a non-directional tie.

I use the constraint based approach to measure structural hole (Burt 1992), which is computed as

$$\left(p_{ij} + \sum_{q} p_{iq}\, p_{qj}\right)^2, \quad q \neq i, \qquad j,$$

Where p_{ij} is the proportional strength of i's relationship with j, p_{ij} is the proportional strength of i's relationship with q, and p_{qj} is the proportional strength of q's relationship with j. UCINET VI was used to calculate these measures (Borgatti et al., 2002). The constraint structural hole index measures the extent to which time and energy is concentrated within a small and denser network. Thus, higher constraint structural holes coefficient means lower levels of knowledge brokering, whereas lower levels of constraint structural holes coefficient is related to higher structural hole capabilities. In order to facilitate the interpretation of the results I measure knowledge broker equals to one minus the constraint structural hole coefficient. Finally, in order to reflect the cross knowledge broker dimension of problem-solving in the scientific and engineering context, I used the AIV structural hole coefficient of the CSV problem solver for problems that emerged in the CSV context and the CSV structural hole coefficient of the AIV problem solver for problems that emerged in the AIV context. For example, for a problem occurred in 2013 in the CSV context, I used the structural hole coefficient of the problem solver in the AIV network in 2012. If the constraint structural hole coefficient is equal to 0.10, the value that entered to the regression is 0.9.

Controls

Problem Importance is included in order to consider the priority that the ALMA organization gave to the focal problem. Problem importance is measured as a binary variable equal to one if the problem was registered as either blocker, critical or major problem in the JIRA system, and zero if the problem was registered as either of normal or minor importance.

Problem Information. The more information is shared about the problem, the more the likelihood of solving the problem is (Baer et al., 2012). On the other hand, too much information could lead to fewer efforts by potential contributors to engage in the solution of the problem (Haas et al., 2015). Problem information was coded as the number of words included in the description of the problem written by the individual who reported the problem in the JIRA system.

Problem Complexity. Consistent with prior research (e.g. Macher, 2006; Nickerson and Zenger, 2004), the total components involved in the problem description was used as a measure of complexity, taking values from one to five. For instance, if a problem was related to the antennas, the correlator and the front-end components, that problem will receive a value of three, implying that the problem is more complex than if the problem had only been related to the antennas.

Solver Problem Load. The number of problems that an individual is assigned to solve can affect the time the individual might dedicate to the solution of the focal problem, affecting the chances of solving the problem (Haas et al., 2015). The variable is calculated as the total problems the focal solver has been assigned to solve in the year the problem was reported.

Initial Boundary Object. By using work arrangements that are material, such as graphs, images, spreadsheets, the problem reporter might either help to achieve a better understanding of the problem on behalf of those who do not have the same professional background (Starr, 2010). Initial boundary object is a binary variable equal to one if a document, such as a graph, figure or spreadsheet was attached to the problem description in the JIRA system by the problem reporter, 0 otherwise.

Problem Attention. There was an option in the JIRA system, called “watchers”, for people that did not necessarily want to contribute to the problem’s solution, but were interested in following up its management by the individuals that effectively were engaged in its solution. I measure problem attention as the number of individuals that clicked in the option “watchers” on each problem.

Contributor Breadth. I measure the breadth of the contribution to solve the focal problem as the log value of the total number of individuals that share a comment in the problem comment forum in the JIRA system. The variable is specified in log form to take account of highly skewed distribution of individuals’ contributions.

Contributor Depth. I measure the depth of the contribution to solve the focal problem as the total number of comments posted in the focal problem forum in the JIRA system, divided by the number of contributors.

Problem Finder. The individuals that reported the problem, measured as dummy variables for each individual who reported a problem, are included to take into account the relationship between the formulator characteristics and problem solving effectiveness (Baer et al., 2012).

Assignee Affiliation. Dummy variables indicating the solver's affiliation, including ALMA, NRAO, ESO, NAOJ and other institutions involved in the construction and testing of the telescope array.

CSV and AIV Phase Contributor: I control for prior experience in each phase. For each context, I measure context phase contributor by creating a binary variable equal to one if the individual was involved in problem solving or tasks activities in the prior year in the context where the focal problem occurred, and zero otherwise.

All regressions include year time dummy variables to control the effect of time trending changes on problem solving effectiveness.

5.4.3. Estimation

The dependent variable in the regressions is problem-solving effectiveness. This variable has two alternatives values: zero and one. Thus, I employ logit binomial models to predict the probability of solving a problem based on the independent variables. The main advantage of using this type of estimation is that the predictive output values is limited to 0 and 1, a result that is not possible to obtain by using ordinary least square (OLS) estimations. Since I employ logit models and my goal is to compare the effect of different predictors across groups, scientific and engineering, I estimate separate equations for each group, as recommended by Hoetker (2007) for these cases, instead of using an interaction variable multiplying a dichotomous context variable, with 0 for engineering context and 1 for scientific context, by the three independent variables. The problem with examining cross-group changes in a variable's effect by making it interact it with a dummy variable for group membership and estimating the resulting equation for all observations is that there is a single error term, ε_i, which forces the unobserved variation for both groups to be equivalent. This is not necessarily true for the sub-samples chosen in any study (Darnell, 1994). The consequence is that the regressions can incorrectly show results that are the contrary to the actual relationship between the variables under study (Hoetker, 2004).

When models are estimated separately for each group, it is possible to compare the statistical significance of the coefficients across groups. This procedure is satisfactory since the coefficients and standard errors are consistent within each group (Hoetker, 2007). Since the same variable is significant in both groups and I want to compare their significances, I first need test whether there is a difference in unobserved variation across groups (Allison, 1999). If there are differences between the unobserved variations in the two groups, I can employ a test to find whether at least one of the coefficients differs across groups in order to compare the relative significance of each independent variable between the scientific and engineering contexts (Allison, 1999; Hoetker, 2004). When comparing one independent variable and finding that it is significant in only one of the groups, the interpretation can be done straightforwardly without needing to employ supplemental tests (Hoetker, 2007).

5.5. Results

Table 1a and 1b present the descriptive statistics and correlations for all variables included in the analyses for scientific and engineering contexts, respectively. On average, 60 percent of the problems were solved in less than a year after they were reported in the scientific phase and 46 percent in the engineering phase. Considering the three explanatory variables, on average, approximately 21% of the observations in the scientific phase sample and 10% of the observations in the engineering phase sample were assigned to the same person who reported the problem. Moreover, the phase spanners variable was higher in the scientific phase (0.8 vs. 0.7), and scientific phase knowledge brokers was slightly lower than engineering phase knowledge broker (0.85 vs. 0.86).

Table 4: Descriptive Statistics and Correlations CSV Context Sample

	Variable	Mean	s.d.	1	2	3	4	5	6	7	8	9	10	11	12
1	Problem-Solving Effectiveness	0.60	0.49												
2	Problem Importance	0.41	0.49	0.18											
3	Problem Information	138.10	193.71	0.05	0.13										
4	Problem Complexity	1.36	0.64	-0.11	0.17	0.12									
5	Solver Problem Load	15.85	14.34	-0.13	-0.02	0.00	0.00								
6	Problem Attention	4.73	4.06	-0.15	0.19	-0.03	0.21	-0.04							
7	Initial Boundary Object	0.16	0.37	-0.13	0.04	-0.06	-0.01	-0.10	0.36						
8	Involvement Breadth	1.49	0.72	0.15	0.34	0.09	0.27	-0.17	0.49	0.25					
9	Involvement Depth	2.66	1.38	0.10	0.22	0.00	0.22	-0.09	0.39	0.27	0.45				
10	Problem Finder-Keeper	0.21	0.41	0.14	0.00	0.01	0.04	-0.17	0.08	-0.05	0.05	0.07			
11	Same Phase Contributor	0.87	0.22	-0.06	-0.09	0.16	0.05	-0.30	0.01	0.17	-0.02	0.10	0.16		
12	Phase Spanners	0.80	0.23	-0.05	-0.02	0.05	0.11	-0.37	0.06	0.01	-0.03	0.08	0.13	0.68	
13	Cross Knowledge Broker	0.85	0.20	-0.15	0.03	0.06	0.12	-0.01	0.12	0.11	0.02	0.09	0.13	0.58	0.57

Number of observations 498. Correlation coefficients greater than 0.03 or less than -0.03 are significant at p<.05.

Table 5: Descriptive Statistics and Correlations AIV Context Sample

	Variable	Mean	s.d.	1	2	3	4	5	6	7	8	9	10	11	12
1	Problem-Solving Effectiveness	0.46	0.50												
2	Problem Importance	0.10	0.30	0.06											
3	Problem Information	330.06	558.71	0.02	-0.10										
4	Problem Complexity	1.08	0.32	0.04	0.09	0.00									
5	Solver Problem Load	16.42	11.90	-0.09	-0.17	0.02	-0.03								
6	Problem Attention	0.47	1.11	0.04	0.27	-0.01	0.22	-0.06							
7	Initial Boundary Object	0.25	0.43	0.02	0.08	-0.03	0.12	-0.15	0.19						
8	Involvement Breadth	1.03	0.71	0.14	0.27	-0.01	0.16	-0.17	0.46	0.26					
9	Involvement Depth	1.99	1.12	0.10	0.18	0.01	0.25	-0.11	0.32	0.22	0.22				
10	Problem Finder-Keeper	0.10	0.30	0.08	0.06	-0.07	0.08	-0.25	0.01	0.12	-0.03	0.10			
11	Same Phase Contributor	0.89	0.31	0.09	0.00	0.01	0.06	-0.05	0.12	0.03	0.22	-0.02	0.07		
12	Phase Spanner	0.70	0.22	0.06	-0.07	0.01	0.00	0.00	0.10	0.11	0.12	0.08	0.12	0.63	
13	Cross Knowledge Broker	0.86	0.14	-0.04	0.02	0.02	0.08	0.21	0.10	0.00	-0.05	0.10	-0.03	-0.11	-0.11

Number of observations 570. Correlation coefficients greater than 0.03 or less than -0.03 are significant at p<.05.

Table 6 presents the logit results for problem solving effectiveness for both the scientific and engineering phase sub-sample. I conducted hierarchical regression analyses and entered control variables first (Models 1), followed by problem finder-keeper variable (Models 2), same phase contributor (Models 3), phase spanners (Models 4), cross knowledge broker (Model 5) and all the explanatory variables at the same time (Models 6). In all the regressions, I controlled for problem formulator, problem solver affiliation and years using categorical dummy variables (coefficients are not shown for parsimony). I tested for multicollinearity by computing the variance inflation factors (VIFs) and found that they were between 1.08 and 7.54 and 1.05 and 6.35 for the scientific and engineering phase, respectively, below the recommended ceiling of 10 (Chatterjee and Price, 1991), suggesting that multicollinearity is not a major concern in our analysis.

Table 6: Logistic Results Predicting Problem-Solving Effectiveness in CSV and AIV Phases

	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6	
	CSV	AIV	CSV	AIV	CSV	AIV	CSV	AIV	CSV	AIV	CSV	AIV
Problem Importance	1.01***	0.78**	1.03***	0.79**	1.00***	0.84**	1.00***	0.82**	1.07***	0.03	1.09***	0.08
	(0.21)	(0.28)	(0.21)	(0.28)	(0.21)	(0.28)	(0.21)	(0.28)	(0.29)	(0.39)	(0.29)	(0.39)
Problem Information	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Problem Complexity	-0.55***	-0.07	-0.58***	-0.05	-0.54***	-0.08	-0.54***	-0.04	-0.61**	-0.41	-0.64**	-0.35
	(0.16)	(0.32)	(0.16)	(0.32)	(0.16)	(0.32)	(0.16)	(0.32)	(0.20)	(0.39)	(0.20)	(0.39)
Solver Problem Load	0.00	-0.01*	0.00	-0.01**	-0.01	-0.01*	-0.01	-0.01*	-0.01	-0.02+	0.00	-0.02*
	(0.01)	(0.00)	(0.01)	(0.00)	(0.01)	(0.00)	(0.01)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)
Problem Attention	-0.14***	-0.14+	-0.14***	-0.14+	-0.14***	-0.15+	-0.14***	-0.14+	-0.15**	0.03	-0.16***	0.02
	(0.04)	(0.08)	(0.04)	(0.08)	(0.04)	(0.08)	(0.04)	(0.08)	(0.05)	(0.11)	(0.05)	(0.11)
Initial Boundary Object	-0.79**	-0.13	-0.76**	-0.13	-0.80**	-0.15	-0.80**	-0.23	-0.83*	-0.38	-0.78*	-0.46+
	(0.25)	(0.15)	(0.25)	(0.15)	(0.25)	(0.15)	(0.25)	(0.16)	(0.35)	(0.24)	(0.35)	(0.25)
Involvement Breadth	0.52**	0.34**	0.51**	0.33**	0.50**	0.33**	0.50**	0.34**	0.75**	0.41**	0.85***	0.32*
	(0.17)	(0.12)	(0.17)	(0.12)	(0.17)	(0.12)	(0.17)	(0.12)	(0.23)	(0.16)	(0.24)	(0.16)
Involvement Depth	0.22*	0.09	0.21*	0.10	0.22*	0.10	0.22*	0.12+	0.21+	0.24*	0.19+	0.25*
	(0.09)	(0.07)	(0.09)	(0.07)	(0.09)	(0.07)	(0.09)	(0.07)	(0.11)	(0.10)	(0.11)	(0.10)
Problem Finder	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Problem Solver Affiliation	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Problem Finder-Keeper			0.51*	-0.36							0.65+	-0.39
			(0.25)	(0.30)							(0.34)	(0.37)
Same Phase Contributor					-0.65	0.52**	-0.64	0.87***			-0.15	-0.01
					(0.49)	(0.18)	(0.56)	(0.21)			(0.13)	(0.01)
Phase Spanner							-0.01	-0.58***			0.16	1.19***
							(0.29)	(0.17)			(0.13)	(0.35)
Cross Knowledge Broker									-1.73*	0.23	-2.28*	0.85
									(0.83)	(0.71)	(1.06)	(0.74)
Constant	0.83	0.16	0.70	0.22	0.88	-0.07	0.87	-0.18	3.16**	1.62	2.49*	0.79
	(0.83)	(0.69)	(0.84)	(0.69)	(0.83)	(0.69)	(0.83)	(0.70)	(1.01)	(1.19)	(1.05)	(1.19)
Number of Observations	846	1,059	846	1,059	846	1059	846	1059	498	570	498	570
LogLikelihood	-450	-670	-448	-670	-449	-666	-449	-660	-248	-341	-244	-335
AIC	1,044	1,433	1,042	1,433	1044	1426	1046	1416	610	764	608	756

+p<0.10, * p<0.05, **p<0.01, *** p<0.001

The results in Models 1 indicate that problem importance does positively affect problem solving effectiveness in both scientific and engineering phases (Models 1, p<0.001 and p<0.01, respectively), according to what should be expected. The coefficients for problem information for both scientific and engineering phase are not significant (Models 1 CSV and AIV, p>0.10). Furthermore, problem complexity negatively affects problem solving effectiveness in the scientific phase, but not in the engineering phase (Models 1, p<0.001 and p>0.10, respectively). This finding for complexity is unexpected, as higher levels of complexity should decrease the chances of solving a specific problem, regardless the context where the problem was found. Regarding the effect of the number of problems the problem solver is responsible to fix, the results show that higher levels of problem solver load does not affect problem solving in the scientific phase, but it does in engineering phase (Models 1, CSV and AIV $p>0.10$ and $p<0.05$, respectively). Moreover, higher levels of problem attention from potential contributors negatively affect problem solving (Models 1, CSV and AIV, $p<0.001$ and $p<0.10$ respectively). The negative and significant coefficients in this variable might be interpreted as higher attention levels in a problem could be a sign of problem difficulty.

The results for initial boundary object suggest that using material tools as graphs and figures when the problem is reported prevent its effective solution in the scientific phase (Model 1 CSV, $p<0.001$), becoming a blocker object to the problem's solution (DiMarco, 2011). The results for boundary object on problem solving effectiveness in the engineering phases is not significant (Model 1 AIV, $p>0.10$). The coefficients for involvement breadth for both scientific and engineering phases are positive and significant (Models 1, $p<0.01$ and $p<0.01$, respectively). Finally, for involvement depth, only in the scientific context it has a positive effect on problem solving effectiveness (Models 1, $p<0.05$ and $p>0.10$, respectively).

Hypothesis 1 suggested that problem finder-keeper is positively associated with problem-solving effectiveness in both the CSV and AIV contexts. The results are mixed: while problem finder keeper was significant in the CSV context (Model 2 CSV, $p<0.05$), problem finder keeper was non-significant in the AIV context (Model 2 AIV, $p>0.10$). Hypothesis 2 proposed a major role of problem finder-keeper on problem solving effectiveness in the CSV environment in comparison to the AIV environment. The positive effect of problem finder-keeper in the scientific context coupled with the lack of a significant effect in the engineering phase context supports Hypothesis 2.

Hypothesis 3 argued that CSV-AIV phase spanners facilitate problem solving effectiveness on the CSV and AIV contexts. In order to test this hypothesis, I first included the variable CSV and AIV phase contributor in Models 3 to control for prior experience in the phase where the problem arose. In Model 3 for the CSV sample, prior experience in scientific context problems is not significant for problem solving effectiveness (Model 3 CSV, $p>0.10$). This result is interesting because it shows that if problem solvers have prior experience in problems occurring in the CSV context, they will not be in a better position to solve the problem in comparison to individuals who have just begun trying to solving problems in the CSV context. Based on the insights gathered in the interviews from the qualitative part of this study, this result could be explained by the novel and heterogeneity of problems emerging in this phase. In addition, since many CSV contributors from the best research institutions all over the world came for a short term to help in this phase and did not have prior experience in the CSV phase, they were so capable in their fields of research that it would compensate for their lack of experience at ALMA.

In contrast, Model 3 AIV suggests that having prior problem-solving experience in the AIV context positively affects problem solving effectiveness in AIV context. This is because problems in the engineering context were highly repetitive over time, so having prior problem-solving experience in the AIV phase could give the problem solver better chances to find a solution.

I did not find support for the effect of phase spanners for the CSV sample (Model 4 CSV, $p>0.10$), nor for the relationship between CSV-AIV phase spanner for the AIV context. In fact, although the coefficient is significant, the sign is negative (Model 4 AIV, $p<0.001$), suggesting that if the problem solver had prior experience in both CSV and AIV contexts it decreases the likelihood of solving the problem. Consequently, Hypothesis 3 and 4 are not supported.

Hypothesis 5 proposed that problem solver's higher levels of knowledge brokering in the AIV context negatively affects problem solving effectiveness in CSV context. As Model 5 CSV shows, we found a significant and negative coefficient for the independent variable (CSV, $p<.05$), supporting Hypothesis 5. However, Hypothesis 6 - that predicted a positive effect between problem solver's knowledge brokering in CSV context positively affecting problem solving effectiveness in AIV contexts - was not supported (Model 5 AIV, $p>0.10$).

Robustness Tests

Several robustness tests were undertaken to check the sensitivity of the results. First, alternative controls were included in the models, such as continuous time trend variable instead of year dummies variables and using solver problem characteristics instead of reporter problem characteristics dummies variables. These alternative analyses yielded consistent results for the hypothesized variables as those shown in the results table presented above. Second, for the hypotheses related to the scientific phase only, I included a control variable that considers how well defined the focal problem was[3], predicting that more structured problems have higher chances to be solved (Simon, 1962; Fernandes and Simon, 1999; Macher, 2006). As expected, a well-defined problem was positively related to problem solving effectiveness. The inclusion of this variable did not affect the results for the hypotheses associated with the scientific phase. Third, I employed a probit

[3] This variable was not included in the main models since there was not information available for this variable in the engineering phase subsample.

estimation for each regression in the CSV and AIV phases. As in the other robustness checks, the results were consistent with the ones reported in the result section.

Chapter 6: Discussions and Conclusion

6.1. Discussion

This dissertation helps shed light on how different communities of knowledge collaborate to solve problems occurring in the construction and implementation of big science project initiatives. Successful development of scientific and innovation initiatives of this type are made possible thanks to the increased support in the last decades and financing from funding agencies as well as research institutions, which are investing billions of dollars to study scientific questions that "normal science" has been unable to respond so far. By exploring the case of the ALMA Telescope Array, this dissertation sketched out in the processes scientists and engineers are involved to achieve effective problem solving activities when they face different organizational contexts influenced by scientific and engineering logics.

This dissertation began with the assumption that the distinction between scientific and engineering contexts in organizations is critical for problem solving processes activities and the tools used by the people involved. Next, I discuss the contribution of this study and its findings for future research on problem solving, boundary spanning mechanisms and science and technology big science project literature.

The findings make three salient key points regarding the relationship between boundary spanning mechanisms, problem solving episodes and scientific and engineering contexts. The first is that a problem finder-keeper is related to problem solving effectiveness in scientific but not in engineering contexts. Second, scientific-engineering phase spanners are not related with effective ways to solving problems in organizations where different communities of knowledge collaborate. Third, engineering cross-knowledge brokers negatively influence problem solving in scientific environments, as proposed in this dissertation, but knowledge brokering in scientific environment is not related with problem solving in engineering contexts.

6.1.1. The Role of Problem Finder-Keepers

Through this study, I advance the current research on problem solving and problem formulation processes (Nickerson and Zenger, 2004; Nickerson, Yen, Mahoney, 2012,). Although these streams of research focus on mechanisms to improve each of these processes, this work examines the effect of individuals who are capable of bridging the different knowledge and informational spaces of these two processes on problem solving effectiveness. Likewise, by exploring the influence of problem finder-keepers, I expand our understanding on the advantages of boundary spanners to the problem-solving processes context, which has not been explored so far in the collaboration mechanism literature. Overall, this type of boundary spanning mechanism matters: problem finder-keepers enhance the chances of solving problems, at least in scientific environments. Research on other modes of boundary spanning mechanisms between problem formulation and problem solving spaces are needed to develop a more robust research of collaboration mechanisms and their influence on problem solving outcomes.

This result has important managerial implications in that it sheds light on the effect that problem finder-keepers can have on problem solving effectiveness, by replacing organizational structure design elements when they are more related to an organic type of structure (Burns and Stalker, 1961). This study suggests that when managers lead organizations where different communities of knowledge collaborate, facing heterogeneous problems, and the organizational structure does not have clear hierarchies and procedures and rules are not well diffused, handing problem-solving to the problem finders could help to improve the rate of problem solving effectiveness in the organization.

Likewise, problem formulation is a key process for the effective development of organizations that engage in innovation and technological activities (Dunbar, 1996; Lyles, 1990). The process to identify the right problem to solve considers different emergent strategies that will lead to better solutions for the organization (Lifshitz-Assaf, 2015). Hence, having people specialized in this process might benefit the organization. Based on the findings of this study, when an organization has clearly defined rules and procedures, allowing information between problem formulation and problem solving to flow effectively, separating the roles of individuals formulating or framing the problem from the individuals who will be responsible of solving the problem could be beneficial, as it is unnecessary to use boundary spanning mechanisms to connect these spaces. Thus, problem finders can instead focus on improving the problem formulation and finding.

This result has also implications for the growing phenomenon of open and distributed innovation initiatives (e.g. Chesbrough, 2003; West and Lakhani, 2008). Scholars interested in this area of innovation research have suggested that when problems have high levels of hidden knowledge, the best way to approach problem-solving activities is by implementing different types of open innovation initiatives (Felin and Zenger, 2014). Likewise, it has been argued that problem seekers, who do not belong to the organization, are dispersed all over the world and freely engage in problem solution activities, are positively related to problem solving effectiveness (Lifshitz-Assaf, 2015). This study sheds light on the benefits making the problem finder responsible of coordinating the problem-solving efforts. Thus, since to the increment the open innovation projects developed by different types of organizations, problem finder-keepers might be good complements to problem seekers if the organizational structural elements are unable to connect the formulation and the problem-solving spaces.

6.1.2. Phase Spanners and Knowledge Brokers on Problem Solving Effectiveness

The model results show that scientific-engineering phase spanners are not beneficial for problem solving activities. In the case of phase spanners in problem solving in scientific contexts, I did not find any relationship. This result could be explained by the sum of two facts. First, scientific problems at ALMA, in the commissioning and science verification phase, were diverse and were generally unrelated to prior problems addressed in this phase. Second, phase spanner was conceived as a problem solver with prior experience in both contexts. Hence, prior experience in the scientific and engineering phases might not have been very useful to face those unprecedented and novel problems. Moreover, based on the results obtained from the qualitative information collected in this study, boundary-spanning capabilities able to bridge scientific and engineering domains did not necessarily come from participation in both types of phases in the construction of ALMA. Instead, this capability could be sourced in the problem solvers' prior experience prior to their engagement in the ALMA organization. In addition, it could be a consequence of having educational background in both engineering and scientific areas.

The second point regarding phase spanner is that if problem solvers in engineering contexts had prior experience in both environments, there is a negative relationship with problem solving effectiveness. This result highlights that it is much more important to focus only on engineering problems than having collaborated in scientific contexts in the past. This result is surprising because scientific-engineering phase spanners can offer information about knowledge and identification of people skills from the science field, which could contribute to solving a problem (Rosenberg and Kline, 1985). However, participating in scientific contexts also requires time and effort that could be invested in increasing learning and experience in the engineering context. Because problems in the engineering context are more repetitive and it is easier to build from solution implemented in the past (Vincenti, 1993), prior experience in the same context will be of particular importance when problems emerge from the engineering side. Overall, this finding regarding the relationship between phase spanners over problem solvers imply that managers from big science projects - and from initiatives where scientist and engineers collaborate within an engineering context - should primarily try to keep engineering problem solvers dedicated to only to tasks and problems occurring on this environment. However, it would be interesting if future studies could differentiate the influence of boundary spanners on problem solving by comparing difficult problems to easier ones. Qualitative findings based on interviews and the written records from the JIRA systems suggest that when a very difficult problem arises, people in engineering contexts tend to turn up to the scientific side at ALMA, which is in line with the chain linked model, proposed by Rosenberg and Kline (1985).

Regarding the effect of cross knowledge broker in problem solving effectiveness, the analysis provides evidence that this type of knowledge network dimension does not have the same effect in different contexts. As expected, based on knowledge networks, boundary spanning mechanisms and science and technology literature, I found that engineering context knowledge broker negatively affects problem solving effectiveness in scientific contexts. This finding adds to prior research on boundary spanning mechanisms, which has associated the presence of boundary spanners to higher levels of innovation outcomes (e.g. Allen, 1984; Tushmann, 1977). By focusing on the type of cross knowledge network that a problem solver needs to develop in order to improve the likelihood of fixing a problem, I found that not all boundary-spanning activities lead to better problem solving outcomes. Instead, the results show that only engineering-scientific context phase spanners that have a close and dense group of partners in the engineering side will be associated to problem solving effectiveness in scientific contexts. Based on knowledge network literature (Ahuja, 2000; Hansen, 1999), this is explained because boundary spanners with restricted networks might have higher chances of convincing people from their engineering side network to collaborate with time and effort to solving scientific problems, than if the individual has a diversified and sparse network in the engineering context.

Contrary to theoretical expectations, scientific context cross knowledge brokers do not affect problem solving effectiveness in engineering contexts. This result is surprising because problem solvers from the engineering context having diverse connections in the scientific phase should benefit from different streams of knowledge disperse through the scientific network. However, this result can be linked with the findings regarding scientific-engineering phase spanners, which shows that phase spanners are negatively related to problem solving effectiveness in engineering contexts. Thus, the finding suggests that if the phase spanner trying to solve problems from the engineering context is also a knowledge broker in the scientific context, he/she will not influence better problem solving outcomes.

The study's findings help shed light on prior research on knowledge networks. By empirically studying the context where knowledge broker characteristics are effective for organizational outcomes - in this case problem solving effectiveness -, I advance on the need to research on contingency conditions that make the relationship between knowledge networks and outcomes differ. As Phelps et al. (2013) has argued, engaging in studies that compare these types of relationships in different institutional contexts may contribute to explain some of the inconsistent results in existing knowledge network research. I pose that this study is a positive step in this direction.

6.2. Conclusion

The ALMA project was able to combine different projects conceived in three different continents. ALMA managers, scientists and engineers achieved to make 66 high precision antennas, which were constructed with different types of cutting edge technologies to work together in one of the most hostile regions of the world. Its operations have allowed advancement in our understanding of star formation, the evolution of galaxies and the ability to look at sites in the universe that have never been explored before. It is amazing that this initiative is not only critical for advancing astronomy and engineering, but also provides to management insights of invaluable usefulness, by studying how scientists and engineers solve problems in such a challenging environment.

This dissertation explores the question of which boundary spanning mechanisms affect the effective solution of problems under different organizational contexts. By combining collaborating mechanisms and knowledge networks along with problem formulating and solving research, I identified mechanisms that can be effective for solving problems under different organizational contexts. By focusing on the development of the

Atacama Large Millimeter/Submillimeter Array (ALMA), I employ the online knowledge-management platform used by ALMA personnel to solve problems along with qualitative information gathered in a span of three years, to shed light on how different communities of knowledge collaborate to solving diverse problems. I add to our understanding about how scientists and engineers employ different boundary spanning mechanisms to transfer and create knowledge to solve problems as they emerge in both scientific and engineering phases.

Overall, this study makes three main contributions to advance problem-solving research, boundary spanning and science and technology literature. First, I examine different types of boundary spanning mechanisms, depending on the type of boundary these type of individual bridge, and their impact on effective problem solving. I expand the notion of boundary spanners to: a) the boundaries individuals need to span between the activities related to the discovery of specific problems, and the activities related to problem-solving that emerge overtime, conceptualized as problem finder-keeper; b) different phases within an innovation initiative, and c) the influence on problem solving effectiveness of having higher levels of knowledge brokering in networks that are external to the problem's location, which was conceptualized as cross-knowledge brokers.

Secondly, it advances our understanding regarding problem-solving episodes by studying particular organizational contexts, scientific and engineering, as a contingency aspect to consider when establishing better collaborative mechanisms in order to achieve effective problem-solving practices. I found that the problem finder-keeper is related to problem solving effectiveness in scientific but not in engineering contexts. Moreover, the results show that scientific-engineering phase spanners are not related with effective ways to solving problems in organizations where different communities of knowledge collaborate. Lastly, engineering cross-knowledge brokers negatively influence problem solving in scientific environments, but knowledge brokering in scientific environment is not related with problem solving in engineering contexts. These findings support the argument that not only the collaboration mechanisms are relevant, but also where the problem emerges is key to develop the right type of boundary spanning mechanisms for fixing what is problematic in the organization.

Finally, this research helps to understand the actions engineers and scientists take once they interact and solve heterogeneous problems during the development of Big Science Projects. In addition to the above-mentioned theoretical contributions for problem solving and boundary spanner literature, this dissertation also provides guidance to Big Science Project managers. While it may be enticing to encourage the participation of "boundary spanners" as one of the most important means to achieve solutions where people from different professions participate, having new forms of boundary spanners might be of special benefit for problem solving effectiveness. Moreover, managers need to take into account that encouraging particular types of collaboration mechanisms might be better for specific contexts in the development of these types of projects.

Several extensions of this research are possible to both build on its findings and unravel some of the unanswered questions. This dissertation is based on a rich collection of qualitative and quantitative data. Nevertheless, the results of this study were influenced by the nature of the information available from the construction of the ALMA Telescope Array. Thus, limitations to the analysis performed should be considered when interpreting and applying its findings. First, the sample used in this study is composed of problem solving episodes gathered from the online knowledge-management platform employed by the ALMA Telescope Array - a mode through which people can communicate and collaborate to solve problems. However, there are other instances of communication where people can collaborate to solve problems in organizations, such as formal meetings, informal conversations in the work place and communication through phone and email. Despite the case of ALMA, where the use of the online knowledge management system was strongly enforced by the management structure, it must be acknowledged that problem solving process also occurs when other communication alternatives are used. Future research on multiple modes of communication upon mutual collaboration of communities of knowledge can offer additional insights in the role of boundary spanning mechanisms regarding problem solving effectiveness.

Second, Big science projects are temporary organizations (Lundin, and Söderholm, 1995). One of the characteristics of these types of organizations is that contributors who participate in those initiatives work for a limited time. For this reason, networks formed during the development of these projects should tend to be more dynamic in comparison to more stable organizations, such as firms and research institutions. Thus, an extension of this study to other types of organizations, such as firms with an active strategy regarding innovation and technology, could be useful to advance the development of more robust theories on problem solving and collaboration mechanisms.

Third, I focus on two phases in the construction of a Big Science Project that resemble a scientific and engineering context. However, there are many phases in the development and implementation of these types of initiatives. While the findings in this study may apply to some of the scientific and engineering phases, they may not be generalizable to others. For instance, from qualitative results in this dissertation based on the interviews conducted at ALMA, astronomers recognized that efficiency was not only a concern in engineering contexts, but it is also critical for science operation phase. Consequently, it would be interesting to examine whether the different boundary spanning mechanisms studied in this dissertation have the same effects on problem solving effectiveness in Big Science Projects' operational phases. By doing so, future studies could expand the boundary conditions of problem solving and collaboration mechanisms studied in this dissertation, which are based on scientific and engineering context, to differentiate development/construction contexts from operational contexts.

Fourth, when evaluating boundary-spanning mechanisms on problem solving effectiveness, I focus on problem solver in three different dimensions of boundary spanning mechanisms that can be present or not in the person assigned to fix the problem in question. Nevertheless, problem solvers engage in problem solving activities along with a group of people that contribute also in this process. This issue is somewhat controlled in the quantitative part of this study by including two variables of breadth and depth involvement in the problem-solving process, which were measured by counting the number of people and the total average of comments made by each person to the problem's solution. However, how problem contributors can bridge knowledge boundaries to effectively solve problems is not explored in this dissertation. In this regard, Zhao and Anand (2013) propose that collective bridges, conceived as "a set of direct interunit ties connecting the members of the source and the recipient units" (Zhao and Anand, 2013, page 1,514) could replace the role of boundary spanners. Thus, to study how problem solver's boundary spanning mechanisms either complement or supplement the group's bridge mechanisms for problem solving effectiveness will enhance our understanding about the sources of problem solving effectiveness in the organization. Overall, I call for further research to confirm and expand the theoretical contributions and findings to provide a better understanding of problem solving activities in organizations involved in innovation and science and technology initiatives.

This dissertation explored a question that is of interest for scientific project managers facing heterogeneous problems arising in different organizational contexts, where individuals coming from diverse professional backgrounds are engaged. Increasingly, other organizations that not big scientific and technological projects are also dealing with similar situations. Firms are getting more complex, attracting collaborators who come from different backgrounds and need to work together, and deal with problems in different environments. I believe that this research regarding ALMA and their scientists and engineers' collaboration mechanisms adds to our overall understanding of problem solving activities. I hope it also stimulates new questions and ideas for future exploration that can be studied in different environments and organizations.

7. References

Ahuja, G. (2000). Collaboration networks, structural holes, and innovation: A longitudinal study. Administrative science quarterly, 45(3), 425-455.

Aghion, P., Dewatripont, M., & Stein, J. C. (2008). Academic freedom, private-sector focus, and the process of innovation. *The RAND Journal of Economics*,*39*(3), 617-635.

Alavi, M., & Leidner, D. E. (2001). Review: Knowledge management and knowledge management systems: Conceptual foundations and research issues. MIS quarterly, 107-136.

Ali, A., Gittelman, M. (2016). Research Paradigms and Useful Inventions inMedicine: Patents and licensing by clinical and basic scientists in AcademicMedical Centers.

Allen, T. J. (1966). Studies of the problem-solving process in engineering design. IEEE Transactions on Engineering Management, (2), 72-83.

Allen, T. J. (1984). Managing the flow of technology: Technology transfer and the dissemination of technological information within the R & D organization (Book). *Research supported by the National Science Foundation. Cambridge, Mass., MIT Press, 1977. 329 p*.

Allison, P. D. (1999). Comparing logit and probit coefficients across groups. Sociological methods & research, 28(2), 186-208.

ALMA Organization. (2015) ALMA Inauguration Heralds New Era of Discovery [Press Realease]

ALMA, (2016) retrieved from http://www.almaobservatory.org.

Arora, A., & Gambardella, A. (1994). The changing technology of technological change: general and abstract knowledge and the division of innovative labour. Research policy, 23(5), 523-532.

Atlassian, (2016). Retrieved from https://www.atlassian.com/software/jira.

Autio, E. (2014). Innovation from big science: enhancing big science impact agenda.

Autio, E., Kenney, M., Mustar, P., Siegel, D., & Wright, M. (2014). Entrepreneurial innovation: The importance of context. Research Policy, 43(7), 1097-1108.

Baba, Y., Shichijo, N., & Sedita, S. R. (2009). How do collaborations with universities affect firms' innovative performance? The role of "Pasteur scientists" in the advanced materials field. Research Policy, 38(5), 756-764.

Baer, M., Dirks, K. T., & Nickerson, J. A. (2013). Microfoundations of strategic problem formulation. Strategic Management Journal, 34(2), 197-214.

Barley, S. R. (1996). Technicians in the workplace: ethnographic evidence for bringing work into organizational studies. Administrative Science Quarterly, 404-441.

Barley, S. R., & Kunda, G. (2001). Bringing work back in. Organization science, 12(1), 76-95.

Baron, J. (1988). Thinking and Deciding. Cambridge University Press, New York.

Boisot, M. (Ed.). (2011). *Collisions and Collaboration: The Organization of Learning in the ATLAS Experiment at the LHC*. Oxford University Press.

Borgatti, S. P., Everett, M. G., & Freeman, L. C. (2002). Ucinet for Windows: Software for social network analysis.

Brooks H. (1994), "The Relationship between Science and Technology", Research Policy 23 477-486.

Burns, T. E., & Stalker, G. M. (1961). The management of innovation. University of Illinois at Urbana-Champaign's Academy for Entrepreneurial Leadership Historical Research Reference in Entrepreneurship.

Burt, R. S. (1992). Structural holes: The structure of social capital competition. MA: Harvard University Press, Cambridge.

Burt, R. S. (2004). Structural holes and good ideas1. American journal of sociology, 110(2), 349-399.

Byckling, E., Hameri, A. P., Pettersson, T., & Wenninger, H. (2000). Spin-offs from CERN and the case of TuoviWDM. *Technovation*, *20*(2), 71-80.

Carlile, P. R. (2002). A pragmatic view of knowledge and boundaries: Boundary objects in new product development. Organization science, 13(4), 442-455.

Carlile, P. R. (2004). Transferring, translating, and transforming: An integrative framework for managing knowledge across boundaries. Organization science, 15(5), 555-568.

Chatterjee, S., & Price, B. (1991). Regression diagnostics. New York.

Chesbrough, H. (2003). The logic of open innovation: managing intellectual property. California Management Review, 45(3), 33-58.

Collins, H., Evans, R., & Gorman, M. (2007). Trading zones and interactional expertise. *Studies in History and Philosophy of Science Part A*, *38*(4), 657-666.

Collins, F. S., Morgan, M., & Patrinos, A. (2003). The Human Genome Project: lessons from large-scale biology. *Science*, *300*(5617), 286-290.

Daft, R. (1983). Organization theory and design. Cengage learning.

Darnell, A. C. (1994). A dictionary of econometrics. Books.

Davies, A., & Brady, T. (2000). Organisational capabilities and learning in complex product systems: towards repeatable solutions. *Research Policy*,*29*(7), 931-953.

De Solla Price, D. J. (1965). Is technology historically independent of science? A study in statistical historiography. *Technology and Culture*, 553-568.

Di Marco, M. K. (2011). The Roles and Impacts of Boundary Spanners and Boundary Objects in Global Project Networks (Doctoral dissertation, COLUMBIA UNIVERSITY).

Di Marco, M. K., Alin, P., & Taylor, J. E. (2012). Exploring negotiation through boundary objects in global design project networks. Project Management Journal, 43(3), 24-39.

Dougherty, D., & Dunne, D. D. (2011). Organizing ecologies of complex innovation. Organization Science, 22(5), 1214-1223.

Dunbar, K. (1996). How scientists think: Online creativity and conceptual change in science. In T.B. Ward, S.M. Smith, & S.Vaid (Eds.) Conceptual structures and processes: Emergence, discovery and Change. APA Press. Washington DC.

Dunbar, K. (1998). Problem solving. W. Bechtel, G. Graham, eds. A Companion to Cognitive Science.

Einstein, A., & Infeld, L.,(1938). The gravitational equations and the problem of motion. Annals of Mathematics, 65-100.

Engwall, M. (2003). No project is an island: linking projects to history and context. *Research policy*, *32*(5), 789-808.

ESO (2015), retrieved from http://www.eso.org/public/teles-instr/.

Felin, T., & Zenger, T. R. (2014). Closed or open innovation? Problem solving and the governance choice. Research Policy, 43(5), 914-925.

Fernandes, R., & Simon, H. A. (1999). A study of how individuals solve complex and ill-structured problems. Policy Sciences, 32(3), 225-245.

Fleming, L., Mingo, S., & Chen, D. (2007). Collaborative brokerage, generative creativity, and creative success. Administrative science quarterly, 52(3), 443-475.

Fleming, L., & Sorenson, O. (2004). Science as a map in technological search.*Strategic Management Journal*, *25*(8-9), 909-928.

Furnari, S. (2014). Interstitial Spaces: Micro-Interaction Settings and the Genesis of New Practices between Institutional Fields. *Academy of Management Review*, amr-2012.

Galison, P., & Hevly, B. W. (Eds.). (1992). *Big science: The growth of large-scale research*. Stanford University Press.

Galison, P. (1997). *Image and logic: A material culture of microphysics*. University of Chicago Press.

Gavetti, G., & Levinthal, D. (2000). Looking forward and looking backward: Cognitive and experiential search. Administrative science quarterly, 45(1), 113-137.

Gieryn, T. F. (1983). Boundary-work and the demarcation of science from non-science: Strains and interests in professional ideologies of scientists. American sociological review, 781-795.

Gittelman, M. (2016). The revolution re-visited: Clinical and genetics research paradigms and the productivity paradox in drug discovery. Research Policy.

Gittelman, M., & Kogut, B. (2003). Does good science lead to valuable knowledge? Biotechnology firms and the evolutionary logic of citation patterns.*Management Science*, *49*(4), 366-382.

Gorman, M. E. (2005). Levels of expertise and trading zones: Combining cognitive and social approaches to technology studies. Scientific and technological thinking, 287-302.

Gorman, M. E. (Ed.). (2012). *Trading zones and interactional expertise: Creating new kinds of collaboration*. Mit Press.

Granovetter, M. (1983). The strength of weak ties: A network theory revisited. Sociological theory, 1(1), 201-233.

Gupta, A. K., & Govindarajan, V. (2000). Knowledge flows within multinational corporations. Strategic management journal, 21(4), 473-496.

Haas, M. R., Criscuolo, P., & George, G. (2015). Which problems to solve? Online knowledge sharing and attention allocation in organizations. Academy of Management Journal, 58(3), 680-711.

Hallonsten, O. (2012). Continuity and change in the politics of European scientific collaboration. *Journal of Contemporary European Research*, *8*(3).

Hansen, M. T. (1999). The search-transfer problem: The role of weak ties in sharing knowledge across organization subunits. Administrative science quarterly, 44(1), 82-111.

Hansen, M. T. (2002). Knowledge networks: Explaining effective knowledge sharing in multiunit companies. Organization science, 13(3), 232-248.

Hevly, B. (1992). Reflections on big science and big history. *Big science: The growth of large-scale research*, 355-363.

Hobday, M. (2000). The project-based organisation: an ideal form for managing complex products and systems?. *Research policy*, *29*(7), 871-893.

Hoetker, G. P. (2004). Confounded coefficients: Extending recent advances in the accurate comparison of logit and probit coefficients across groups. Available at SSRN 609104.

Hoetker, G. (2007). The use of logit and probit models in strategic management research: Critical issues. Strategic Management Journal, 28(4), 331-343.

Iorio, J., & Taylor, J. E. (2014). Boundary object efficacy: The mediating role of boundary objects on task conflict in global virtual project networks. International Journal of Project Management, 32(1), 7-17.

Jeppesen, L. B., & Lakhani, K. R. (2010). Marginality and problem-solving effectiveness in broadcast search. Organization science, 21(5), 1016-1033.

Jonassen, D.H. (2004). Learning to Solve Problems: An Instructional Design Guide. Jossey-Bass, San Francisco, CA.

Kaplan, C. A., & Simon, H. A. (1990). In search of insight. Cognitive psychology, 22(3), 374-419.

Kauffman, S.A. (1993). The origins of order: Self organization and selection in evolution. Oxford University Press, USA.

Kellogg, K. C., Orlikowski, W. J., & Yates, J. (2006). Life in the trading zone: Structuring coordination across boundaries in postbureaucratic organizations.*Organization science*, *17*(1), 22-44.

King, A., & Lakhani, K. R. (2013). Using open innovation to identify the best ideas. MIT Sloan management review, 55(1), 41.

Klahr, D., & Dunbar, K. (1988). Dual space search during scientific reasoning. Cognitive science, 12(1), 1-48.

Kline, S. J., & Rosenberg, N. (1986). An overview of innovation. The positive sum strategy: Harnessing technology for economic growth, 14, 640.

Knorr-Cetina, K. (1999). Epistemic cultures: How scientists make sense.

Kogut, B. (2000). The network as knowledge: Generative rules and the emergence of structure. Strategic management journal, 21(3), 405-425.

Lacetera, N. (2009). Different missions and commitment power in R&D organizations: Theory and evidence on industry-university alliances. Organization Science, 20(3), 565-582.

Leonardi, P. M. (2011). When flexible routines meet flexible technologies: Affordance, constraint, and the imbrication of human and material agencies. MIS quarterly, 35(1), 147-167.

Levin, D. Z. (1999). Transferring Knowledge Within the Organization in the R & D Arena.

Levin, D. Z., & Cross, R. (2004). The strength of weak ties you can trust: The mediating role of trust in effective knowledge transfer. Management science, 50(11), 1477-1490.

Levina, N., & Vaast, E. (2005). The emergence of boundary spanning competence in practice: implications for implementation and use of information systems. MIS quarterly, 335-363.

Lifshitz-Assaf, H. (2015, January). From Problem Solvers to Solution Seekers: Knowledge Boundaries Permeation at NASA. In Academy of Management Proceedings (Vol. 2015, No. 1, p. 14234). Academy of Management.

Lopez, B., Jager, R., Whyborn, N. D., Knee, L. B., & McMullin, J. P. (2012, September). Assembly, integration, and verification (AIV) in ALMA: series processing of array elements. In SPIE Astronomical Telescopes+ Instrumentation (pp. 84490P-84490P). International Society for Optics and Photonics.

Lundin, R. A., & Söderholm, A. (1995). A theory of the temporary organization.*Scandinavian Journal of management*, *11*(4), 437-455.

Lyles, M. A. (1990). A research agenda for strategic management in the 1990s. Journal of Management Studies, 27(4), 363-375.

Lyles, M. A., & Mitroff, I. I. (1980). Organizational problem formulation: An empirical study. Administrative Science Quarterly, 102-119.

MacDuffie, J. P. (1997). The road to “root cause”: Shop-floor problem-solving at three auto assembly plants. Management Science, 43(4), 479-502.

McFadyen, M. A., Semadeni, M., & Cannella Jr, A. A. (2009). Value of strong ties to disconnected others: Examining knowledge creation in biomedicine. Organization science, 20(3), 552-564.

Macher, J. T. (2006). Technological development and the boundaries of the firm: A knowledge-based examination in semiconductor manufacturing. Management Science, 52(6), 826-843.

March, J. G., & Simon, H. A. (1993). Organizations revisited. Industrial and Corporate Change, 2(1), 299-316.

McCray, W. P. (2004). *Giant telescopes: Astronomical ambition and the promise of technology*. Harvard University Press.

Merton, R. K. (1973). The sociology of science: Theoretical and empirical investigations. University of Chicago press.

Morrison, E. W. (2002). Newcomers' relationships: The role of social network ties during socialization. Academy of management Journal, 45(6), 1149-1160.

National Science Foundation. (2014) National Science Foundation Celebrates Inauguration of Atacama Large Millimeter/submillimeter Array (ALMA) in Chile [Press release].

NRAO, (2015) retrieved from https://public.nrao.edu/

Nelson, R. R. (2001). The coevolution of technology and institutions as the driver of economic growth. *Frontiers of Evolutionary Economics, Competition, Self-organization and Innovation Policy*, 19-30.

Nelson, R. R. (2003). On the uneven evolution of human know-how. *Research Policy*, *32*(6), 909-922.

Nerkar, A., & Paruchuri, S. (2005). Evolution of R&D capabilities: The role of knowledge networks within a firm. Management Science, 51(5), 771-785.

Newell, A., & Simon, H. A. (1972). Human problem solving (Vol. 104, No. 9). Englewood Cliffs, NJ: Prentice-Hall.

Nicolini, D., Mengis, J., & Swan, J. (2012). Understanding the role of objects in cross-disciplinary collaboration. Organization Science, 23(3), 612-629.

Nightingale, P. (1998). A cognitive model of innovation. Research policy, 27(7), 689-709.

Nightingale, P. (2004). Technological capabilities, invisible infrastructure and the un-social construction of predictability: the overlooked fixed costs of useful research. *Research Policy*, *33*(9), 1259-1284.

Nickerson, J. A., & Zenger, T. R. (2004). A knowledge-based theory of the firm—The problem-solving perspective. Organization science, 15(6), 617-632.

Nickerson, J., Yen, C. J., & Mahoney, J. T. (2012). Exploring the problem-finding and problem-solving approach for designing organizations. The Academy of Management Perspectives, 26(1), 52-72.

Nochur, K. S., & Allen, T. J. (1992). Do nominated boundary spanners become effective technological gatekeepers?[technology transfer]. Engineering Management, IEEE Transactions on, 39(3), 265-269.

NRAO, (2010). Millimeter array MMA proposal.

NRAO, (2015). Retrieved from https://public.nrao.edu/telescopes/alma.

Orlikowski, W. J. (2002). Knowing in practice: Enacting a collective capability in distributed organizing. Organization science, 13(3), 249-273.

Phelps, C., Heidl, R., & Wadhwa, A. (2012). Knowledge, networks, and knowledge networks a review and research agenda. Journal of Management, 38(4), 1115-1166.

Reagans, R., & McEvily, B. (2003). Network structure and knowledge transfer: The effects of cohesion and range. Administrative science quarterly, 48(2), 240-267.

Rosenberg, N. (1994), "Scientific instrumentation and university research", chapter 13 in *Exploring the Black Box,* New York: Cambridge University Press.

Rottner, R. (2015, January). Out of Bounds: Remaking Multiplex Boundaries in a Megaproject. In Academy of Management Proceedings (Vol. 2015, No. 1, p. 13547). Academy of Management.

Sauermann, H., & Cohen, W. M. (2010). What makes them tick? Employee motives and firm innovation. Management Science, 56(12), 2134-2153.

Sauermann, H., & Stephan, P. (2013). Conflicting logics? A multidimensional view of industrial and academic science. *Organization Science*, *24*(3), 889-909.

Sieg, J. H. (2012). Problems on the Boundary: Involving External Service Providers in Organizational Problem Formulation (Doctoral dissertation, ETH).

Simon, H. A. (1962). The architecture of complexity (pp. 457-476). Springer US.

Simon, H. A., & Lea, G. (1974). Problem solving and rule induction: A unified view.

Simon, H. A., & Newell, A. (1971). Human problem solving: The state of the theory in 1970. American Psychologist, 26(2), 145.

Smith, W. K., & Tushman, M. L. (2005). Managing strategic contradictions: A top management model for managing innovation streams. Organization science, 16(5), 522-536.

Shore, J., Bernstein, E., & Lazer, D. (2015). Facts and figuring: An experimental investigation of network structure and performance in information and solution spaces. Organization Science, 26(5), 1432-1446.

Star, S. L. (2010). This is not a boundary object: Reflections on the origin of a concept. Science, Technology & Human Values, 35(5), 601-617.

Star, S. L., & Griesemer, J. R. (1989). Institutional ecology,translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social studies of science*, *19*(3), 387-420.

Stephan, P. E. (2012). *How economics shapes science* (Vol. 1). Cambridge, MA: Harvard University Press.

Stern, S. (2004). Do scientists pay to be scientists?. *Management science*,*50*(6), 835-853.

Suchman, M. C. (1995). Managing legitimacy: Strategic and institutional approaches. Academy of management review, 20(3), 571-610.

Thomke, S., Von Hippel, E., & Franke, R. (1998). Modes of experimentation: an innovation process—and competitive—variable. Research Policy, 27(3), 315-332.

Thornton, P. H., & Ocasio, W. (2008). Institutional logics. The Sage handbook of organizational institutionalism, 840, 99-128.

Tsai, W. (2002). Social structure of “coopetition” within a multiunit organization: Coordination, competition, and intraorganizational knowledge sharing. Organization science, 13(2), 179-190.

Tushman, M. L. (1977). Special boundary roles in the innovation process. Administrative science quarterly, 587-605.

Tyre, M. J., & Von Hippel, E. (1997). The situated nature of adaptive learning in organizations. Organization science, 8(1), 71-83.

Vaughan, Diane, (1999), "The Role of the Organization in the Production of Techno-Scientific Knowledge: NASA and the Challenger Accident" Social Studies of Science 29: 913-43.

Vincenti, W. (1993). What engineers know and how they know it. *Analytical Studies from Aeronautical History. The Johns Hopkins University Press Baltimore and London*.

Von Hippel, E. (1976). The dominant role of users in the scientific instrument innovation process. Research policy, 5(3), 212-239.

Vuola, O., & Hameri, A. P. (2006). Mutually benefiting joint innovation process between industry and big-science. *Technovation*, *26*(1), 3-12.

Walsh, J. P., & Dewar, R. D. (1987). FORMALIZATION AND THE ORGANIZATIONAL LIFE CYCLE [1]. Journal of Management Studies, 24(3), 215-231.

Wasserman, S., & Faust, K. (1994). Social network analysis: Methods and applications (Vol. 8). Cambridge university press.

Watts, D. J., & Strogatz, S. H. (1998). Collective dynamics of 'small-world'networks. nature, 393(6684), 440-442.

Webster, A. (2007). Crossing boundaries social science in the policy room. Science, Technology & Human Values, 32(4), 458-478.

West, J., & Lakhani, K. R. (2008). Getting clear about communities in open innovation. Industry and Innovation, 15(2), 223-231.

Zhao, Z. J., & Anand, J. (2013). Beyond boundary spanners: The 'collective bridge' as an efficient interunit structure for transferring collective knowledge. Strategic Management Journal, 34(13), 1513-1530.