

**INTERDISCIPLINARITY AMONG ACADEMIC SCIENTISTS:
INDIVIDUAL AND ORGANIZATIONAL FACTORS**

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**INTERDISCIPLINARITY AMONG ACADEMIC SCIENTISTS:
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LIST OF ABBREVIATIONS

GLM	Generalized Linear Model
IDR	Interdisciplinary Research
IOM	Institute of Medicine
NAE	National Academy of Engineering
NAS	National Academy of Sciences
NIH	National Institutes of Health
NSB	National Science Board
NSF	National Science Foundation
SC	Subject Category
SED	Survey of Earned Doctorates
STEM	Science, Technology, Engineering, and Mathematics
S&E	Science and Engineering
S&T	Scientific and Technical
WOS	Web of Science

SUMMARY

Today when interdisciplinary research (IDR) is becoming increasingly important in generating innovative research results and solving complex problems in academia, discussions of IDR antecedents, processes and outcomes are becoming increasingly important in research policy and sociology of science. This study addresses two primary questions: 1) what individual and organizational factors affect academic scientists' engagement in IDR, 2) what the effects of these factors are in difference disciplines. Drawing on a wide variety of social science theories including studies of academic tenure system, organizational climate theory, theories about women and gender in science and scientific and technical human capital theory, it develops four hypotheses to investigate the effects of tenure system, university climate for IDR, gender, and industry experience on the degree to which individual scientists engage in IDR.

To test the hypotheses, the key work of the study is to address the issue of measuring researcher interdisciplinarity. This study applies Pierce's conceptual model that identifies three types of interdisciplinary activities: borrowing, boundary crossing and collaboration to understand and frame interdisciplinarity. By focusing on production aspects of IDR, it generates two bibliometric indicators to measure scientists' borrowing activities by looking at the reference diversity of scientists' papers published in their own disciplines and scientists' boundary crossing activities by calculating the percentage of scientists' papers published in other disciplines. It further develops two dependent variables: the self-reported percentage of IDR papers which is from researchers' own

estimate of their IDR papers responding to one survey question, and the calculated percentage of IDR papers which is a combination of two bibliometric indicators of scientists' borrowing and boundary crossing activities. Both of the two dependent variables measure the overall degree to which scientists engage in publishing interdisciplinary papers but they are generated based on different techniques – survey and bibliometrics, which improve the reliability of IDR measurement. The study performs regression models on both of the two dependent variables in the full sample of scientists and each discipline to investigate the effects of individual and organizational factors on scientists' IDR.

This study finds that our conventional wisdom about the effects of university tenure and promotion system on scientists' propensity to engage in IDR is outdated. The tenure hypotheses built on previous studies and assumptions are not supported by the research results in most disciplines. Meanwhile, whether females are more drawn to IDR in one discipline actually depends on the prevalence of women in the discipline, indicating that the disciplinary contexts should be considered in investigating the effects of various factors on scientists' IDR. This study suggests science policy makers, funding agencies and university administrators to keep fresh and informed about scientists' research activities and underlying context and take full into account of distinct characteristics of different disciplines when they make or reform policies to encourage IDR work.

CHAPTER 1: INTRODUCTION

Scientific activities are becoming more interdisciplinary (Gibbons, Limoges et al. 1994, Van Rann 2000, Braun and Schubert 2003, Porter and Rafols 2009).

“Interdisciplinarity,” which was seen as a panacea for the reform of higher education in the late 1960s and the 1970s (Weingart 2000, p.25), has become an increasingly important “mode of discovery and education, ... [that has] delivered much already and promised more – a sustainable environment, healthier and more prosperous lives, new discoveries and technologies to inspire young minds, and a deeper understanding of our place in space and time” (NAS/NAE/IOM 2005, p.1).

1.1 The Promise of IDR

The term “Interdisciplinary”¹ often refers to scientific practice that goes beyond traditional disciplinary boundaries. It is a complex concept and difficult to define. The US National Academies examined the current interdisciplinary practice and the Committee on Facilitating Interdisciplinary Research published a report to provide ideas for defining and measuring interdisciplinarity. In this report, interdisciplinary research (IDR) is defined as:

“A mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or

¹ From the conceptual perspective, some researchers draw clear distinctions between multidisciplinary, interdisciplinarity and transdisciplinarity. In empirical studies, however, the distinctions between these terms are often blurred. As many scholars did in their research, this study chooses to treat interdisciplinary as a general term.

bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or field of research practice” (NAS/NAE/IOM 2005, p.26).

Many researchers have also attempted to define IDR in different ways (Brewer and Lövgren 1999, Lattuca 2003, Aram 2004, Aboelela, Larson et al. 2007). Even though so far there is still no agreement of what IDR means, the importance of interdisciplinary research (IDR) for advancing knowledge has been widely recognized in recent decades. First, research across disciplinary boundaries may be more innovative and creative, because it brings together people from different fields and backgrounds (Chen 1986, Palmer 1999, Klein 2000, Carayol and Thi 2005, Cummings and Kiesler 2005, De Boer 2006, Reich and Reich 2006, Kim, Kim et al. 2008, Blackwell, Wilson et al. 2009). Collaboration between different disciplines can generate new ideas, develop new research approaches, and improve analysis of complex problems (Reich and Reich 2006). Hence, IDR is expected to be more likely to generate innovative research results.

Second, IDR can tackle many complex problems, such as environmental and public health issues, that cannot be addressed by single disciplines (Rose 1986, Foray and Gibbons 1996, Jeffrey 2003, Morillo, Bordons et al. 2003, Thi and Lahatte 2003, Klein 2004, Reich and Reich 2006, Aboelela, Larson et al. 2007, Pennington 2008, Schmidt 2008). Today, with the increasing complexity of society, several research problems are becoming multidisciplinary or interdisciplinary in nature: addressing them often requires the knowledge integration from multiple different disciplines, because single disciplines may solve only one or a few components of these complex problems (Hagoel and Kalekin-Fishman 2002, Braun and Schubert 2003). The Committee on Facilitating

Interdisciplinary Research, which was built by the National Academies, summarized four main drivers for IDR: “the inherent complexity of nature and society, the desire to explore problems and questions that are not confined to a single discipline, the need to solve societal problems, and the power of new technologies” (NAS/NAE/IOM 2005, p.2). Moreover, IDR is becoming more important as national science and research policies place increased emphasis on problem-oriented research, which often crosses boundaries between disciplines (Hattery 1986, Weingart and Stehr 2000).

As a result, funding agencies, national scholarly associations, universities, and research centers have made great efforts to promote IDR. The National Institutes of Health (NIH) made interdisciplinarity a priority in its Roadmap, a new strategic plan for over \$2.1 billion in future NIH funding, and funded several IDR centers (e.g., Interdepartmental Neuroscience Center) “as a means of integrating aspects of different disciplines to address health challenges that have been resistant to traditional research approaches” (NIH 2007, p.1). In 2004, the National Science Foundation (NSF) selected five priority areas for significant investment for the next several years, most of which are important interdisciplinary areas (NSF 2004). In 2008, the National Science Board (NSB) assessed the role of NSF in supporting IDR and reported this assessment to the Congress. This report has clearly indicated that “support of interdisciplinary research occurs throughout NSF and is an important aspect of NSF’s contribution toward the Nation’s scientific and engineering research productivity and infrastructure” (NSB 2008, p.8). For example, the term “interdisciplinarity” appeared in 35 percent of the 342 funding programs that were active on the NSF website on July 10, 2008 (NSB 2008). Moreover, NSF’s FY 2012 budget request to Congress not only stated that one of its three

major goals is “transform the frontier,” emphasizing the role of NSF in “supporting fundamental, interdisciplinary, high-risk, and transformative research and education,” but also proposed a large investment on IDR: for example, \$12 million on a new effort “Integrated NSF Support Promoting Interdisciplinary Research and Education (INSPIRE)” and \$96 million on a multidisciplinary research “Science and Engineering Beyond Moore’s Law (SEBML)” (NSF 2012, p.2). Likewise, a few national professional associations like the American Chemical Society also place important emphasis on IDR and provide sponsorship for it (Kane 2003, Rhoten 2004).

Several universities have created instruments and incentives for researchers and practitioners to promote interdisciplinary work (Gershon 2000, Rhoten and Parker 2004, AAU 2005, Holley 2009, Jacobs and Frickel 2009, Klein 2010, Novak, Zhao et al. 2014). The interdisciplinary task force of the Association of American Universities (2005) presents many universities’ practical examples of how they developed interdisciplinary education and research programs, funded interdisciplinary seminars, created additional faculty positions for interdisciplinary centers, coordinated interdepartmental collaboration, reformed tenure evaluation policies, and provided fellowships and assistantships for graduate students in interdisciplinary programs. Brint (2005) asked 144 provosts and vice presidents of 89 American universities how they encouraged IDR: more than 75 percent said their institutions hired star academics to lead IDR, and over 80 percent reported the introduction of interdisciplinary graduate training programs in their institutions. Sá (2008) also noted that 18 Research Extensive Universities had established funding programs for supporting interdepartmental collaboration by 2005 and

a few universities (e.g., Duke University and the University of Southern California) have changed their policies in faculty promotion and evaluation in order to encourage IDR.

1.2 Research Questions and Motivation

IDR is becoming increasingly attractive because of its potential for addressing complex problems and generating innovative research results. NSF (2012, p.2) also clearly identifies “the increasingly interdisciplinary nature of modern science and engineering.” Therefore, IDR is not only driven strongly by the support from funding agencies, university administrators and professional associations, but also valued widely among academic faculty (Jacobs and Frickel 2009). But not every scientific researcher is interested in IDR. Especially, there are numerous epistemic and administrative challenges facing interdisciplinary researchers in the scientific community (Heberlein 1988, Hagoel and Kalekin-Fishman 2002, Kandiko and Blackmore 2008, Jacobs and Frickel 2009, Bindler, Richardson et al. 2012, Sievanen, Campbell et al. 2012); for example, they need to overcome the barriers from incompatibility among disciplines with different cultures, methods and languages, and their research work may lack support from home departments which value disciplinary research more.

Porter, Roessner et al. (2006, p.188) stress that “policymakers must address the issue of how best to nurture IDR at multiple levels — science policy, institutional strategy, research lab and individual training.” A few preliminary studies indicate that the degree of IDR differs by individual (Carayol and Thi 2005, van Rijnsoever and Hessels 2011), institution (Sá 2008) and discipline (Morillo, Bordons et al. 2001, Rinia, van Leeuwen et al. 2002, Morillo, Bordons et al. 2003, Porter, Cohen et al. 2007). It implies that addressing the issue requires attention to both individual factors and

contextual conditions. In this context, the research empirically investigates two primary questions: *1) What are the individual and organizational factors affecting academic scientists' interdisciplinarity? 2) What are the effects of these factors in different scientific disciplines?*

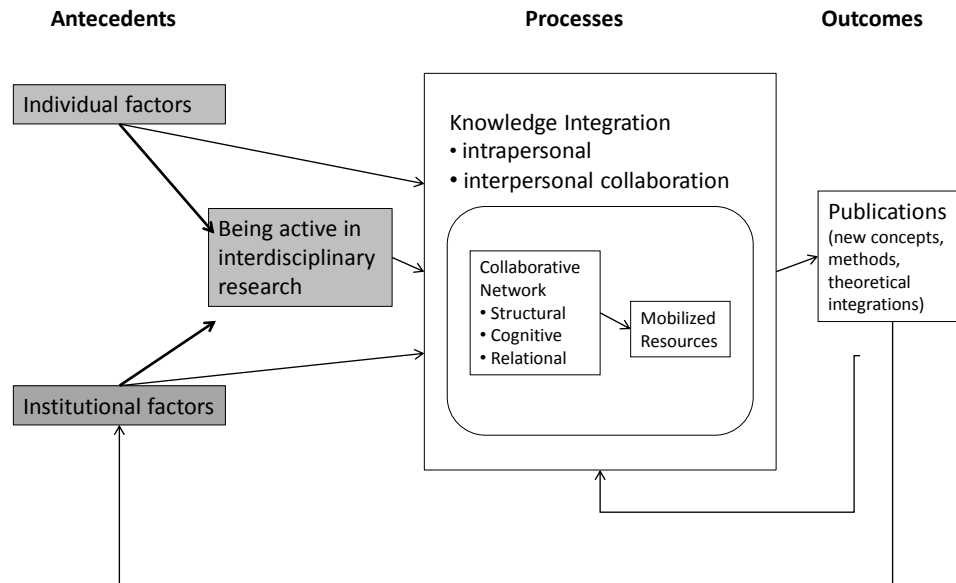
1.2.1 Theoretical Motivation

There are many reasons that motivate me to study the two questions. First, the research wants to bridge the gap in current studies on IDR and makes theoretical contributions to IDR literature. With the increasing interdisciplinary thinking in scientific research, numerous IDR studies have been done in order to better understand interdisciplinarity. But we still have very limited knowledge of the factors impacting the propensity of individual scientists to engage in IDR, which is shown in the grey parts in the framework of evaluating IDR (Figure 1), initially developed by Stokols and his colleagues (Stokols, Fuqua et al. 2003).

Currently, scholars of studying IDR have made great efforts to explore IDR processes and outcomes. Studies on interdisciplinary collaboration address many issues on interdisciplinary collaborative process. Researchers investigated interdisciplinary collaborative mechanisms, strategies and tools, and analyzed team-based behavior in collaborative process underlying IDR (Qin, Lancaster et al. 1997, Palmer 1999, Jeffrey 2003, Cummings and Kiesler 2005). These studies improve our understanding of interdisciplinary collaborative process, and provide implications for those who fund, manage, and work in IDR on how to manage, support and encourage research collaboration across disciplinary boundaries. Meanwhile, several scholars also study IDR outcomes. By “identifying and characterizing the interdisciplinary content within

the total output of research” (Wagner, D. et al. 2009, p.3), researchers focus on mapping and measuring the interdisciplinary relations between disciplines (Rip and Courtial 1984, Tijssen 1992, Tomov and Mutafov 1996, Morillo, Bordons et al. 2001, Porter and Rafols 2009, Chi and Young 2013, Roessner, Porter et al. 2013). Their studies provide important information for us to track the changes of disciplines over time, to identify the appearance and development of newly emerging interdisciplinary areas of research, and to compare the interdisciplinary behavior of different research areas (Morillo, Bordons et al. 2001). In addition, some researchers examine the impact of IDR outputs (Steele and Stier 2000, Rinia, van Leeuwen et al. 2001, Levitt and Thelwall 2008, Larivière and Gingras 2010), which yields “crucial information about research performance that can be seen as complementary to peer opinion” (van Raan and van Leeuwen 2002, p.614).

So far the two streams of research have addressed many issues about IDR processes and outcomes. Yet, less is known about IDR antecedents. More specifically, we have very limited understanding of individual and organizational factors affecting scientists’ IDR, because the existing studies on the issue are mainly built on conventional perceptions of facilitators and barriers of IDR, and relied on limited empirical evidence. By drawing on a wide variety of social science theories including organizational climate theory, studies of academic tenure system, scientific and technical (S&T) human capital theory and theories about women and gender in science, this study is seeking to address the issue in a more systematic and coherent way. The research will extend our knowledge of individual-level factors and organizational conditions affecting researchers’ propensity to engage in IDR, but also contribute to some research issues which have been widely discussed in the sociology of science (e.g., studies of women in science).



Note: It is adapted from Stokols et al. 2003

Figure 1 Model of Evaluating Interdisciplinary Science

Moreover, in investigating the effects of individual and organizational factors on scientists' interdisciplinarity, this study takes into account the distinctions among disciplines, which have been neglected by many existing studies on IDR. "Disciplines are not only intellectual but also social structures, organizations made up of human beings with vested interests based on time investments, acquired reputations, and established social networks that shape and bias their views on the relative importance of their knowledge" (Weingart and Stehr 2000, p.xi). As intellectual, organizational and social contexts of science, "disciplines dominate academic careers" (Blackmore and Kandiko 2011, p.124) and thus are important for understanding academic scientists' research activities. When one studies science and evaluates scientists' work, he must take into account the different research conditions of different disciplines (Melin 2000).

For example, several studies have found that the degree to which academic scientists' research is oriented to industrial application differs across disciplines (Okubo and Sjöberg 2000, Dietz and Bozeman 2005, Gulbrandsen and Smeby 2005, Lin and Bozeman 2006). The gender composition of scientists differs by scientific discipline: women are better represented in biological sciences but are less represented in most S&E areas (NSF 2010a).

IDR varies in different disciplinary contexts. Empirical studies found that disciplinary openness differs by discipline (Thi and Lahatte 2003), and the types and levels of interdisciplinary collaboration vary among different disciplines (Qin, Lancaster et al. 1997). A recent NSF report discussing trends in interdisciplinary dissertation research shows that the percentage of doctoral graduates conducting IDR differs by discipline (Millar and Dillman 2012). Data from the Higher Education Research Institute's 2004-05 National Survey, consisting of responses from 40,670 professors at 421 institutions, indicate that faculty working in engineering, the humanities, and the social sciences are more likely to do interdisciplinary work than faculty in the natural sciences (Hurtado and Sharkness 2008). All these findings imply that it is necessary to take into account the distinctions between disciplines when analyzing individual and institutional factors affecting scientists' interdisciplinarity. Also, the different effects of these factors in different disciplinary contexts should become policy considerations for universities and policy makers.

1.2.2 Method Motivation

There are two method motivations for this study. First, a few prior studies have examined the impact of personal factors such as gender and personal career experience

on IDR (Mellin and Winton 2003, Thi and Lahatte 2003, Carayol and Thi 2005, van Rijnsoever and Hessels 2011). But the studies on this issue show some significant limitations: most concentrated narrowly on discussing interdisciplinarity of scientists within a single lab, program, institution or college, limiting their generalizability. With a broader sample, this study will expand the research scope to analyze the interdisciplinarity of academic scientists in six scientific disciplines (biological sciences, chemistry, computer science, earth and atmospheric sciences, electrical engineering, and physics) across 151 Carnegie-designated Research Extensive Universities.

Second, this study addresses the issue of measuring individual researcher's interdisciplinarity. There are two main limitations within current measures of IDR. The first limitation is that almost all empirical studies only rely on bibliometric approach to measure IDR, and very few studies combine the use of bibliometrics with other traditional research approaches such as survey to address measurement issue of IDR. "Bibliometrics is a generic term for quantitative analyses of relevant characteristics of the contents of scientific and technological texts, mostly across a set of research publications" (Tijssen 1992, p.27). There are many advantages associated with bibliometric measures of IDR. For example, bibliometrics is based on a wealth of quantitative data of publication records; it can apply various methods such as co-author, co-word, or co-citation analysis to examine the degree of one paper's IDR; and it produces relevant bibliometric indicators to provide empirical insights into research activities. As Porter, Roessner et al. (2006, p.190) state, bibliometric studies on IDR "enable characterization of various research elements in terms of their degree of interdisciplinarity – papers, researchers, collections of researchers or institutes."

However, each bibliometric method has its limitations (See Appendix), which may lead to many measurement errors. For instance, co-word analysis is only applicable in homogeneous fields of study because the classification schemes (key words) are a bit narrow. To address this limitation, therefore, this study adopts a combined use of bibliometrics and survey to develop multiple measures of researchers' interdisciplinarity.

The other limitation with current measures of interdisciplinarity is almost all IDR indicators developed in existing studies only capture one dimension of IDR. For example, co-author indicator of IDR only measures co-authoring pattern of researchers from different disciplines, and reference indicator of IDR only measures the diversity of knowledge cited by interdisciplinary researchers. These indicators do not measure the overall degree to which one research engages in IDR. To solve the problem, this study develops a more comprehensive indicator to capture multiple dimensions of scientists' interdisciplinary activities.

1.2.3 Practical Motivation

From the practical perspective, this study explores factors that may impact academic scientists' likelihood of engaging in IDR, and wishes to suggest an implication of the empirical results for science policy makers and university administrators who wish to promote IDR in university settings, for instance, in establishing effective graduate training programs and reforming relevant faculty policies like hiring strategies for potential target researchers in interdisciplinary science.

Compared to scientists in other sectors, academic scientists often encounter more barriers when conducting interdisciplinary activities. Government laboratories and industry centers have flexible structures and orientation towards more specific goals like

national security, which “force vigorous and effective interdisciplinary work” (Metzger and Zare 1999, p.942). Universities, however, are discipline-oriented. Using a survey and telephone interviews, Bruce, Lyall et al. (2004) found that researchers often saw interdisciplinary background as a disadvantage in universities but an advantage in the industry sector. Traditional academic departments follow disciplinary lines, insist on disciplinary integrity, and support disciplinary research (Saxberg, Newell et al. 1981, Heberlein 1988, Blau 1994, Clark 1995, DE MEY 2000, Adams, Carter et al. 2008, Wagner, D. et al. 2009). Such orientations make it difficult for scientists to receive interdisciplinary training and limit the conduct of research across academic disciplines in university environments (Kast, Rozenzweig et al. 1970, Swanson 1986, Golde and Gallagher 1999, Hollingsworth and Hollingsworth 2000, Nash, Collins et al. 2003). Lack of departmental support is an important impediment to IDR in academic institutions. In a survey of nine directors of interdisciplinary Ph.D. programs, Harris, Giard et al. (2004, p.50) found and asked them to list challenges, in which “difficulties with departmental support” was identified as a key challenge facing their programs. Some scholars also argue that IDR may bring fewer rewards and more risks to researchers’ academic career (Bruce, Lyall et al. 2004). On the other hand, university research needs to be responsive to complex social concerns and problems, which often call for IDR. Universities take important responsibilities for providing knowledge and brainpower for IDR development. Academic faculties are the main labor force in scientific research. Recent NSF data also show that 47.1 percent of doctoral scientists and engineers work in educational institutions, compared with 37.2 percent in industry and 9.1 percent in government (NSF

2006). Hence, discussing the research questions in the academic context has policy implications for interested parties seeking to encourage greater interdisciplinarity.

1.3 Structure of the Dissertation

This dissertation is organized in five chapters. Chapter two focuses on literature review and hypotheses development. It first introduces the conceptual model of IDR. This model provides a main basis for studying and measuring the degree of interdisciplinarity in the thesis. Then it discusses intrinsic and extrinsic motivations for researchers to conduct IDR. It reviews a large amount of literature and builds theoretical foundation for hypotheses development. At last, it formulates four hypotheses about individual and organizational factors impacting the degree of interdisciplinarity.

Chapter three describes the data, measures of variables and models for testing hypotheses developed in the third chapter. The most important part of the chapter is to generate IDR indicators and develop two dependent variables to measure the overall degree of IDR. According to the characteristics of the dependent variables, it chooses appropriate regression model to test the relationship of the degree of interdisciplinarity and various factors at individual and institutional level.

Chapter four presents research findings. It makes descriptive analyses of the data, and characterizes interdisciplinary activities of academic scientists in each discipline based on the analyses. It also reports the results of regression models and associated findings in the full sample and across disciplines. It interprets the relationships of dependent variables and independent variables which are statistically significant in the models.

Chapter five concludes the dissertation by summarizing key findings, main theoretical contributions and policy implications of the thesis, identifying the specific limitations and discussing future research directions.

CHAPTER 2: LITERATURE REVIEW

2.1 The Conceptual Model of IDR

The primary question discussed in the research is what individual and organizational factors affect the degree of scientists' IDR. The key issue here is how to understand and frame researchers' interdisciplinary activities, from both conceptual and methodological perspectives. Pierce (1999) developed three conceptual views of individual researchers' IDR (I call it "the conceptual model of IDR" in this study) which can help address this issue. In his study, Pierce sees information transfer as a key element of IDR, because scientists' interdisciplinary activities are conducted mainly through reaching knowledge and information of different disciplines and transferring them into their own work. Pierce identifies the following three ways in the transfer of information:

2.1.1 Borrowing

Borrowing means "researchers borrow theories or methods from other disciplines, importing them into their own disciplinary literature" (Pierce 1999, p.272). The "borrowing" concept has been widely applied in empirical studies to explore the relationships and knowledge flows between scientific disciplines. For example, several scholars have sought to draw a map of science in terms of interdisciplinary relations, through showing knowledge flow or exchange among disciplines, and interdisciplinary linkages across fields (Rivas, Deshler et al. 1996, Van Leeuwen and Tijssen 2000, Rinia, van Leeuwen et al. 2002, van Raan and van Leeuwen 2002). The graphical analysis of

the network of interdisciplinary links between fields can not only assess the entire structure and dynamics between central fields and contributing fields (Tomov and Mutafov 1996), but also provide science and technology policy makers who need to evaluate scientific activities across a variety of fields with useful information on the interaction between disciplines, for example, inform them on questions such as “What are the main features of the interdisciplinary structure?” or “Which are closely related fields?” (Tijssen 1992, p.42) .

From the bibliometric perspective, an interdisciplinary researcher’s borrowing behavior is often reflected in his publications, because references in a paper usually represent the sources of knowledge and information which the paper authors borrow from other researchers (Rafols and Meyer 2007). In some recent studies, researchers adopt references approach to measure the degree of interdisciplinarity (Sanz-Menendez, Bordons et al. 2001, Rafols and Meyer 2007). The underlying logic is by looking at a paper’s references, one can assess the diversity of disciplines from which the paper authors borrow knowledge and information.

2.1.2 Boundary Crossing

Boundary crossing means “researchers publish work in other disciplines, exporting theories or methods to other disciplinary communities” (Pierce 1999, p.272). As Pierce (1999) states, boundary crossing is the most direct means of information transfer, because interdisciplinary scientists themselves are able to have a large control on what are presented to readers. The concept of boundary crossing is applied in many empirical studies, especially in understanding how many different disciplines highly interdisciplinary fields are crossing. For example, to investigate the interdisciplinarity of

nanoscience, Meyer and Persson (1998) used journal classification suggested by Katz and Hicks (1995) to calculate the distribution of nano-papers published in different fields (e.g., Engineering and Materials, and Life Sciences). Boundary crossing can be also applied to analyze the relations or connections between disciplines. When researchers in one discipline frequently publish their papers in certain other disciplines, it shows a close relationship between these disciplines. For instance, scholars study the relation between materials science and physical chemistry, applied physics, polymers and metallurgy by looking at the distribution of material scientists' papers published in these disciplines (Sanz-Menendez, Bordons et al. 2001).

2.1.3 Collaboration

Another way of interdisciplinary information transfer is collaboration. Research collaboration means “the working together of researchers to achieve the common goal of producing new scientific knowledge” (Katz and Martin 1997, p.7). Today scientific research has shifted away from individual activity toward a more collaborative process (Bordons and Gomez 2000) . Such a shift is reflected not only in an increasing number of multiple-authored publications (Beaver and Rosen 1979b, Gordon 1980, Wagner-Döbler 2001), but also on an increasing number of authors per paper (Hicks and Katz 1996, Adams, Black et al. 2005, Frenken, Hölzl et al. 2005). Meanwhile, many researchers identified a variety of factors to account for this shift. For example, Katz and Martin (1997) listed ten important factors, including the specialization of science, changing patterns of public funding, increasing cross-fertilization across disciplines, and so on. Wagner (2005) indicates that the sharing and exchanging of ideas, resources and

data, and the cooperation around equipment are all possible drivers for the increasing research collaboration among scientists.

The importance of scientific collaboration to knowledge creation is also widely acknowledged in the scientific community. Collaborative network ties represent professional resources that can be accessed, mobilized and put into use in scientific knowledge creation, diffusion and transfer. Many studies have demonstrated that scientific collaboration not only enables sharing of ideas, knowledge and resources between scientists, but also contributes to the production of knowledge and scientific innovation, through bringing together researchers within an organization, across organizations, across sectors, or even across countries (Gibbons, Limoges et al. 1994, Katz and Martin 1997, Wagner and Leydesdorff 2005). Moreover, scientific collaboration can improve research productivity (Beaver and Rosen 1979a, Landry, Traore et al. 1996, Thorsteinsdottir 2000, Lee and Bozeman 2005, He, Geng et al. 2009) and research impact (Presser 1980, Diamond 1985, Smart and Bayer 1986, Sauer 1988, Leimu and Koricheva 2005, Figg, Dunn et al. 2006).

Interdisciplinary work may be undertaken not only by an individual scientist who has strong knowledge and expertise in multiple disciplines (Bordons, Zulueta et al. 1999, Palmer 1999, Sigogneau, Malagutti et al. 2005, Rhoten and Pfirman 2007), but also by interpersonal collaboration (Qin, Lancaster et al. 1997, Palmer 1999, Rhoten 2003, Stokols, Fuqua et al. 2003). In his model, Pierce (1999, p.272) defines interdisciplinary collaboration as occurring when “researchers publish work in their own disciplinary literatures authored with members of other disciplines.” In practice, however, collaboration not only means coauthoring, but also includes many other types of

collaborative ties: for example, scientists can collaborate on patent applications, grant proposals, and product development. Therefore, in the conceptual model of IDR, this study sees collaboration in a broader way, not only including co-authorship from different disciplines which could be either in authors' own disciplines or in other disciplines, but also covering more types of working together between scientists from distinct disciplines.

2.1.4 The Relationship between the Three Types of IDR

The three types of IDR are not completely isolated from each other.

Collaboration overlaps with the other two. As Figure 2 shows, borrowing takes place in interdisciplinary researchers' own disciplinary literature, while boundary crossing means publishing in other disciplines. These two are independent of each other.

Interdisciplinary collaboration (grey area) has a larger range. It not only covers co-authorship between researchers in different disciplines, but includes their collaboration on other types. In publishing papers, collaboration has overlaps with borrowing or boundary crossing. For example, one researcher can either work individually or collaborate (co-author) with people from distinct disciplines on publishing interdisciplinary papers in his own fields (borrowing) or in other fields (boundary crossing).

The three types of IDR may or may not be highly correlated. Some interdisciplinary scientists borrow knowledge from other disciplines, collaborate with other scientists from different disciplines, and publish in other disciplinary communities at the same time. Others borrow knowledge from other fields but only publish within their own disciplinary literature. In such cases, if we use different scores to measure their

interdisciplinarity in different types of IDR, they will have very high scores in borrowing but very low in boundary crossing.

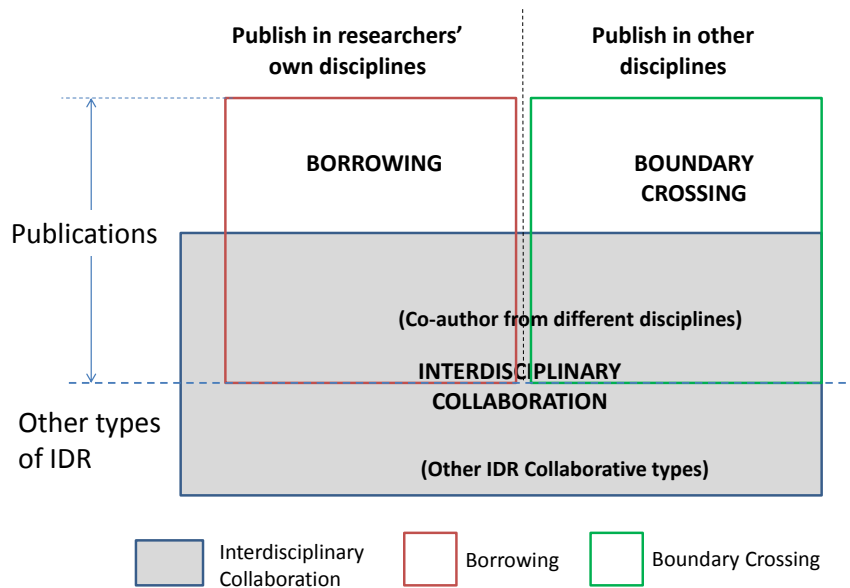


Figure 2 Relationship Between the Three Types of IDR

2.2 Motivation For IDR

So far this chapter has introduced a conceptual model to understand what IDR means in this study, which provides a basis for measuring the degree of interdisciplinarity in later chapter. In the following sections of this chapter, I will focus on reviewing several sets of relevant literature and developing hypotheses. Before doing so, I first discuss the motivation for researchers to work on IDR. The discussion is necessary because of “the importance of motivation in understanding why interdisciplinary activity takes place or does not” (Blackmore and Kandiko 2011, p.127).

Over the past two decades, the scientific system has shifted from traditional ‘Mode I,’ where knowledge is created in a disciplinary, homogeneous, and hierarchical context, to ‘Mode II,’ which emphasizes knowledge produced in the context of application, transdisciplinarity, and research collaboration across organizations, sectors, or even countries (Gibbons, Limoges et al. 1994). In the dynamic scientific environment, a large number of university scientists are becoming more interdisciplinary, especially when IDR is becoming a larger priority for funders, universities, research units and the like. Then, what motivate researchers to work on IDR? Classic motivation theories (Deci 1972, Ryan and Deci 2000) classify the factors that motivate people to perform or work into two broad groups: intrinsic and extrinsic motivation.

2.2.1 Intrinsic Motivation

Intrinsic motivation plays a key role in faculty research activities (Behymer 1974, Finkelstein 1984). Generally, it refers to factors related to the work itself, e.g. “the opportunity for independent thought and action, feelings of worthwhile accomplishment, opportunities for personal growth and development, and job-related self-esteem” (Olsen 1993, p.454). In academic setting, intrinsic motivators include research interests, feelings of satisfaction resulting from exploring research puzzles, and so on. In his study of the behavior patterns of scientists, Merton also states that the behavior of scientists is motivated by their interest in the priority of discovery and their concern with advancing knowledge (Merton 1957, Merton 1970).

IDR activities are different from disciplinary activities in many aspects: they are crossing traditional boundaries; they are more innovative; they are more oriented to practical problems; but meantime they are more challenging. In many cases of

interdisciplinary work, academic researchers often encounter various difficulties and lack sufficient external support. Why are they still enthusiastic about IDR? Intrinsic motivation may be able to explain the cause. After interviewing several academic senior researchers in major research universities who have participated in IDR, Blackmore and Kandiko (2011) found that individuals may be intrinsically motivated to interdisciplinarity, because they enjoy working across different disciplinary fields, or because they love the power of interdisciplinarity in addressing complex and large social problems which cannot be addressed by single disciplinary knowledge. Rhoten (2004, p.8-9) also indicated the intrinsic motivation to IDR in her study. She found that many young researchers are driven to IDR because of their intellectual interests.

In addition, many studies apply personal trait analysis approach to investigate personality characteristics of people who are motivated to conduct interdisciplinary work (Blackwell, Wilson et al. 2009). For example, Klein (1990, p.183) listed several characteristics of interdisciplinary researchers: “reliability, flexibility, patience, resilience, sensitivity to others, risk-taking, a thick skin, and a preference for diversity and new social roles.” Van Rijnsoever and Hessels (2011) believe that interdisciplinary researchers are those who are willing to receive new thoughts and able to make innovative ideas. Bruce, Lyall et al. (2004, p.465-466) argue that researchers working on IDR are people who can tolerate ambiguity and are interested in addressing practical problems. Nash, Collins et al. (2003, p.46) also state that interdisciplinary researchers have “curiosity about what other disciplines offer to addressing the problem..., a willingness to risk venturing outside one’s area of expertise and reveal one’s limits to

collaborators from different fields, and an optimism that the venture can lead to novel findings.”

2.2.2 Extrinsic Motivation

Extrinsic motivation is “the performance of an activity because it leads to external rewards” (Deci 1972, p.113). In university settings, key extrinsic factors include organizational structures and reward systems, organizational support, and salary (Winkler 1982). A survey of 320 faculty members found that tenure and promotion were the top two motivators for doing academic research, especially for junior faculty (Chen, Gupta et al. 2006). Moreover, organizational policies and practices have been found in many empirical studies to have an important impact on scientists’ academic research (Blau 1973, Long and McGinnis 1981, Neumann and Finaly-Neumann 1990, Fox 2001, Fox and Mohapatra 2007). In understanding who are becoming involved in IDR in universities, therefore, one needs to take into account features of the organizations in which interdisciplinary scientists work.

2.3 Organizational and Individual Factors

Discussion of researchers’ motivation for IDR implies that factors at the individual level and the institutional level both play a key role in encouraging scientists to engage in IDR. Therefore, the study intends to address the primary research question – what are the factors affecting academic scientists’ interdisciplinarity from the two perspectives: organizational and individual factors.

2.3.1 Organizational Factors

Science is social-organizational work (Kemelgor and Etzkowitz 2001). The organizational features of scientific research such as promotion and reward systems, and organizational priorities have an important impact on scientific productivity (Crane 1965, Long and McGinnis 1981, Fox and Mohapatra 2007) and scientific careers (Fuchs, von Stebut et al. 2001).

IDR is also an organizational activity. The conduct of interdisciplinary work not only depends on institutional support for financial, human, and material resources, but also requires researchers to be able to establish scientific collaboration across disciplinary boundaries in their organizations to access diverse information and knowledge in different disciplines. Although little empirical work examines the effect of institutional level factors (except tenure) on individual researcher's interdisciplinarity, many scholars have acknowledged that organizational contexts play a key role in stimulating or inhibiting scientists' interdisciplinary research activities (Liscombe 2000, Nash, Collins et al. 2003, Porter, Roessner et al. 2006). The book *Facilitating Interdisciplinary Research*, for instance, indicated that "individual researchers involved in interdisciplinary research require a supportive environment that permits them to work in multiple disciplines and departments and to be fairly evaluated and rewarded for both their interdisciplinary and their disciplinary work" (NAS/NAE/IOM 2005, p.61). Whether an institution values IDR, whether it can provide sufficient internal and external resources for more complicated, more difficult, and more time-consuming interdisciplinary work, whether it encourages faculty to develop links with other departments, would have a significant impact on its faculty members' interdisciplinary endeavor. Mellin and Winton

(2003) found that work environments including support from institutions and colleagues' receptivity of IDR explained a significant amount of the variance in reported time in interdisciplinary activities. In this study, specifically, I intend to discuss the effects of two organizational factors on scientists' interdisciplinarity: tenure and university climate for IDR.

Organizational Reward Policies – Tenure

University tenure and promotion policies have a significant effect on faculty's attitudes towards IDR, particularly for untenured faculty (Blackmore and Kandiko 2011, p.126). Studying how tenure affects scientists' propensity to engage in IDR leads one to consider the organizational characteristics of university systems that may stimulate or constrain the development of IDR. Studies in the higher education literature have indicated that the tenure system shapes American universities. As the most important prize that the American university promotion system offers, tenure provides university professors with a guarantee of lifetime employment, and thus preserves their academic freedom of intellectual inquiry, teaching, research, and publication (Carmichael 1988, Brown and Kurland 1990, Premeaux and Mondy 1997, McPherson and Morton Owen 1999). In spite of being under increasing attacks in recent years (McPherson and Morton Owen 1999), tenure still "acts as an employment policy adapted to the unique nature of a professor's job, specifically the time and expense required to train the employee to perform the job duties, the highly specialized nature of a professor's responsibilities, and the difficulty in monitoring the professor's work performance" (Adams 2006, p.70).

Tenure is a key factor that shapes academic faculty behavior and impacts faculty research preferences (Marchant and Newman 1994). Untenured scientists usually try

their best to keep their research work and academic performance in line with the requirements of university tenure systems, since achieving tenure as soon as possible is the most important goal for almost all young faculty (Tien and Blackburn 1996, Latif and Grillo 2001). Without the security of tenure, junior faculty tend to play it safe and to be conservative (Nir and Zilberstein-Levy 2006). For example, given the bias in traditional evaluation for tenure and promotion which prefers basic science and single discipline research rather than applied research (Siegel, Waldman et al. 2003), junior academic scientists are found to be more likely to devalue commercially relevant scientific research than their tenured counterparts (Boardman and Ponomariov 2007).

The conventional wisdom is that IDR would put untenured researchers' academic careers at risk (Metzger and Zare 1999), because traditional evaluation for promotion and tenure emphasizes the contribution to existing disciplines (Hurtado and Sharkness 2008). In a National Academy of Sciences survey (NAS/NAE/IOM 2005), respondents chose promotion and tenure criteria as the top impediment to IDR in their universities. Another national faculty survey indicated that approximately 80 percent of untenured faculty members engaged in IDR reported stress over the tenure review and promotion process, compared to 70 percent of untenured not working on IDR (Hurtado and Sharkness 2008). Because of "tension between the scientific promise of the interdisciplinary path and the academic prospect of the tenure track" (Rhoten and Parker 2004, p.2046), scientists would prefer to take risks to conduct IDR work after tenure is secured (Kandiko and Blackmore 2008). So scholars believe that untenured faculty members are less likely to do IDR than tenured faculty members (Klein 1996, Carayol and Thi 2005, Blackwell, Wilson et al. 2009). Three reasons may explain it further.

First, IDR is riskier, more complicated, more difficult, and more time-consuming than disciplinary research (Heberlein 1988, Golde and Gallagher 1999, Morgan, Kobus et al. 2003, Nash, Collins et al. 2003, Stokols, Fuqua et al. 2003, Bruce, Lyall et al. 2004, Pfirman 2005, De Boer 2006, Borrego and Newswander 2008, Kandiko and Blackmore 2008, McCoy and Gardner 2012), slowing publication and delaying tenure (Heberlein 1988), because of a number of barriers and challenges to conducting IDR (Bauer 1990, Brewer 1999, Golde and Gallagher 1999, Bruce, Lyall et al. 2004, Haythornthwaite, Lunsford et al. 2006). For example, diversity and heterogeneity among disciplines with differing cultures, methods and languages would increase the complexity of communication and cooperation across disciplines and thus require researchers to spend more time on IDR (Bauer 1990, Brewer 1999, Jewitt and Gorgens 2000, Bruce, Lyall et al. 2004, Reich and Reich 2006, Blackwell, Wilson et al. 2009). Jacobs and Fricke (2009, p.47) also stated that “individual researchers must make extra effort and take on additional risk to pursue IDR without the kind of support that comes easily to researchers who remain within their home disciplines.” Rhoten (2004) found that in their survey, about 30 percent of researchers in the interdisciplinary centers reported that interdisciplinary affiliations were not helpful for and even hindered their careers in some cases. As a result, untenured faculty may be more conservative in choosing to work on IDR, given tenure pressure (Carayol and Thi 2005).

Second, publishing IDR may be problematic (Heberlein 1988, Bruce, Lyall et al. 2004, Pfirman, Martin et al. 2007, Kandiko and Blackmore 2008, He, Geng et al. 2009). Publishing single-author papers in high-ranking disciplinary journals, which is one of the most important promotion and tenure criteria (Nash, Collins et al. 2003), may be more

difficult for interdisciplinary researchers. Interdisciplinarity raises several problems for traditional quality review process; for example, it lacks peer reviewers who are able to understand multiple disciplines (Bruce, Lyall et al. 2004, Laudel 2006, Mansilla, Feller et al. 2006, Blackmore and Kandiko 2011), and reviewers from traditional disciplines may devalue interdisciplinary work beyond their disciplines (Bruce, Lyall et al. 2004, Pfirman 2005, Laudel 2006). These increase the difficulty of publishing interdisciplinary papers in prestigious disciplinary journals. Moreover, although now interdisciplinary researchers have more opportunities and channels to publish their studies than they used to, many interdisciplinary journals do not have high rankings (De Boer 2006) or cannot attract many readers in one's primary field (Nash, Collins et al. 2003). Meanwhile, departments may not value interdisciplinary journals as much as disciplinary journals, which discourages young faculty members who are eager to be promoted (Reich and Reich 2006, Blackwell, Wilson et al. 2009).

Third, tenure, promotion and hiring procedures do not favor IDR because departments are still mainly organized by disciplines (Thi and Lahatte 2003, NAS/NAE/IOM 2005, Payton and Zoback 2007) and university departments' evaluation culture is usually discipline-based (Blackmore and Kandiko 2011). In the university environment, the evaluation and promotion of academic scientists are typically based on a single department. Junior faculty members' engagement in interdisciplinarity would depend highly on their departmental colleagues' support for their tenure and promotion (Lattuca 2001). Adams and her colleagues (2008, p.155) pointed out, based on their own experience, that "one of the biggest obstacles to tenure or promotion for faculty with an interdisciplinary bent is the risk that their senior departmental colleagues either not

understand or not value their work, or will not be so highly motivated to support them when their allegiance to the department and the discipline is less intense.” In some university cases, untenured interdisciplinary faculty members were also found to experience more constraints of tenure reviews, because tenure and promotion review mainly considers papers published in journals within their own disciplines (Stokols, Fuqua et al. 2003). After a series of interviews with the leading interdisciplinary researchers at the Caltech Beckman Institute, Scerri (2000, p.203-212) found that “university hiring procedures work in such a way as to exclude interdisciplinarity” so that many young scientists would “avoid the interdisciplinary path,” because working across two or more disciplines make them suffer disadvantages when they are applying for jobs by any single disciplinary department. Given these reasons, I hypothesize that

H1: Tenured faculty tends to engage in research with a higher degree of interdisciplinarity than untenured faculty.

University Climate for IDR

“Organizational climate is a relatively enduring characteristic of an organization which distinguishes it from other organizations; and (a) embodies members collective perceptions about their organization with respect to such dimensions as autonomy, trust, cohesiveness, support, recognition, innovation, and fairness; (b) is produced by member interaction; (c) serves as a basis for interpreting the situation; (d) reflects the prevalent norms, values and attitudes of the organization’s culture; and (e) acts as a source of influence for shaping behavior” (Moran and Volkwein 1992, p.19).

A university’s climate for IDR reflects the collective perception and attitudes of university administration and its faculty members towards IDR; and the interdisciplinary

climate around the campus also positively influences individual researchers' endeavor for IDR. Better interdisciplinary climates on campus should provide opportunities and encouragement for IDR, and stimulate scientists to work on interdisciplinary areas. For example, Sa (2008) found that top universities receiving NSF interdisciplinary grants are those institutions which are well-known for interdisciplinary culture such as Carnegie Mellon University and those universities which have established strong interdepartmental collaboration climates through formal funding programs. After reading 69 strategic planning documents and interviewing 144 leaders of 89 American research universities, Brint (2005) listed six universities in his sample which have the clearest strategic plans committed to interdisciplinarity, and all of them are among top twenty universities receiving NSF interdisciplinary grants in Sa's research findings. These universities in which interdisciplinary climate tends to prevail not only provide a good platform for their faculty members to conduct interdisciplinary activities, but also provide financial, human and material resources which are particularly needed for interdisciplinary programs (Bruce, Lyall et al. 2004). The university environment that does not cherish IDR ambitions would impact negatively the propensity of scientists to engage in IDR. Kandiko and Blackmore (2008) noted that an important aspect of universities which would hinder IDR is "there was no culture of going outside one's own department and a general lack of knowledge of other fields". Given this, I hypothesize that

H2: Academic scientists in institutions with a better climate for IDR tend to engage in research with a higher degree of interdisciplinarity.

2.3.2 Individual Factors

Gender

The issue of women in science has been discussed and investigated in social studies of science and engineering (S&E) for a long time. With the shift of the scientific system from traditional Mode I to Mode II which emphasizes application, interdisciplinarity and collaboration, researchers are further interested in whether men and women scientists behave differently in new knowledge production systems, given that “men as a group and women as a group can and do differ widely in their practices” (Fox 2001, p.662). Studies have discussed gender differences in engaging in entrepreneurial activity such as technology transfer, patenting (Whittington and Smith-Doerr 2005, Ding, Murray et al. 2006, Link, Siegel et al. 2007, Stephan and El-Ganainy 2007), and in research collaboration (Bozeman and Corley 2004, van Rijnsouwer, Hessels et al. 2008). Some researchers proposed that women may be more drawn to IDR (Kastenhofer and Röggl 2007, Rhoten and Pfirman 2007).

Social scientists and science policy makers pay attention to women’s issues in science for two main reasons. First, women are an important labor force for scientific development (Pearson and Fechter 1994, Hanson 1996, Fox 2010). Attracting more women and underrepresented minorities into S&E can diversify the S&E workforce, which is significant because bringing people with different ideas and backgrounds to science would contribute to innovation and creativity (Xie and Shauman 2003). The second reason is related to “social equity in access to and rewards for professional participation” (Fox 2010, p.998). Fox (1998, 2001) indicated that participation and

rewards in academic scientific professionals should be equal for men and women, because scientific careers should “be open to talent” (Merton [1942] 1973, p.272) .

But the reality is “women as a group remain less well represented and less successful than men in every dimension of the (scientific) career” (Long 2001, p.218): participation, position, performance and recognition (Cole and Zuckerman 1984, Zuckerman 1991, Long and Fox 1995, Levin and Stephan 1998, Gershon 2000, Fuchs, von Stebut et al. 2001, Prpić 2002). The recent NSF statistical data have shown that women are largely under-represented in almost all S&E fields except biological sciences (NSF 2010a). Studies also note that women scientists are lower in academic rank, career outcomes, and salary than men scientists (NAS/NAE/IOM 2007). Several studies of women in science further address various barriers that women face (Long and Fox 1995, Astin and Cress 2003, Fox 2003, Long 2003, Shauman and Xie 2003). A large number of empirical studies attributed the disadvantageous status of women in S&E to structural, organizational, social psychological, and family-related factors (Zuckerman 1991, Sonnert 1999, Xie and Shauman 2003, Fox 2005). These factors should be taken into account for science policy community in order to improve greater equity for both men and women.

Among the discussions of women in science, Rhoten and Pfirman may be the first ones who attempted to examine the gender difference in preference for IDR in a systematic way. They (2007, p.56-60) first characterized IDR activities into four types: “cross-fertilization, team-collaboration, field creation, and problem-orientation.” Corresponding to the four types of interdisciplinary activities, they (2007, p.57) then analyzed how women differ from men in “learning style,” “work preferences,” “career

behaviors,” and “problem-oriented” focus. They (2007, p.59-60) argued that women may be more likely to participate in IDR, because 1) women are “better at assimilating diverse forms of information,” 2) women scientists prefer team work rather than independent work, 3) women scientists prefer to be involved in a new field rather than traditional science, and 4) women scientists prefer to work with people rather than things. Moreover, sociocultural or organizational factors are also taken into account for understanding women in science (Zuckerman 1991, Valian 1999, Fox 2001). In current scientific community, because organizational practice and reward systems often “put women into unequally competitive positions,” women may prefer to choose a relatively “un-crowded” field rather than a traditionally field (Rhoten and Pfirman 2007, p.59-60) .

A few empirical studies also provided preliminary evidence for supporting the argument that women are more likely to work on IDR. Kastenhofer and Roggla (2007) found that female scientists made up a higher proportion of authors in interdisciplinary papers than in disciplinary papers. In their studies of research collaboration at Utrecht University, van Rijnsouwer and Hessels (2011) found that men and women do not differ in disciplinary collaboration but women are engaged in more interdisciplinary collaborations than men are. Millar (2011) noted that female doctoral graduates are generally more likely to conduct IDR in their dissertations than male students, and gender differences are stronger in science, technology, engineering, and mathematics (STEM) fields. Hence, it can be hypothesized that

H3: Female academic scientists tend to engage in research with a higher degree of interdisciplinarity than male academic scientists.

Professional Experience in Industry

Today, the interaction between universities and industry firms is expanding with the growing commercial applicability of scientific technology. Scientific collaboration crossing academy-industry boundaries has been investigated by many researchers (Mueller 2006, Ponomariov 2008, Baba, Shichijo et al. 2009). University-industry ties can improve individual scientists' performance (Gulbrandsen and Smeby 2005, Balconi and Laboranti 2006), contribute to firms' industrial performance (Grossman, Reid et al. 2001), and facilitate the transformation of academic scientists' human capital and social capital into the firm's own scientific networks (Murray 2004).

Career mobility between academia and industry is increasing. Although scientists often experience difficulties such as cultural challenges in their career mobility, they benefit from past experience in a different sector. In S&T human capital theory, developed by Bozeman and his colleagues, professional experience in different sectors is important S&T human capital embodied in individuals, because it provides useful resources, knowledge, skills, and other assets for scientists' and engineers' work, and thus impact their scientific career formation and pattern (Bozeman, Dietz et al. 2001, Bozeman and Corley 2004). Professional experience in industry is also found to contribute to scientists' productivity in terms of inventive patents in empirical studies (Dietz and Bozeman 2005, Lin and Bozeman 2006, Lubango and Pouris 2007).

IDR often has industrial application (Rossini, Porter et al. 1981, Schmoch, Breiner et al. 1994, Scerri 2000). Nanoscale Science and Engineering, as one of the most popular new interdisciplinary technologies, is seen as "leading to new products, new business, new jobs and even new industries" (Huang, Chen et al. 2004, 325). Strong

interactions between university and industry are also found in interdisciplinary areas of science and technology like biotechnology and nanotechnology (Oliver 2004, Libaers, Meyer et al. 2006, Stuart and Ding 2006, Stuart, Ozdemir et al. 2007). Zucker, Darby et al. (2002) indicated that university star bioscientists often work closely with firm scientists, and the scientific publications jointly authored by academic scientists and firm scientists contribute to firm success. In addition, from the perspective of firms, Liebeskind, Oliver et al. found the close collaboration between industrial and university scientists in new biotechnology firms (Liebeskind, Oliver et al. 1996, p.431) .

Given the strong industrial orientation of IDR, are scientists who have worked in industry more likely to engage in IDR than others? Studies have noted that interdisciplinary researchers' career experience may differ from those of disciplinary researchers. For instance, Rhoten and Pfirman (2007, p.56) state that “new cadres and cohorts of interdisciplinary scholars are emerging—scholars whose intellectual objectives, epistemological convictions, and professional strategies may be different from those of their predecessors and orthogonal to many of the disciplinary-based practices of the academy.”

Moreover, empirical studies have also shown that industrial job experience contributes to IDR. Individuals who actively engage in industry-relevant activities are more likely to be funded in new interdisciplinary technologies research (Melkers and Xiao 2010). Industrial ties are found to be an important incentive to individual academic scientists' involvement in IDR (Carayol and Thi 2005). The number of previous firms for which individuals worked is positively related to interdisciplinary research

collaboration but negatively related to disciplinary research collaboration (van Rijnsoever and Hessels 2011). Therefore, I hypothesize that

H4: Academic scientists with industry experience tend to engage in research with a higher degree of interdisciplinarity than those without industry experience.

2.4 Summary

The first chapter has identified the gap this study seeks to bridge: individual and organizational factors affecting scientists' interdisciplinarity. In this chapter, I review literature on IDR and develop four hypotheses about the effects of various factors on scientists' interdisciplinarity.

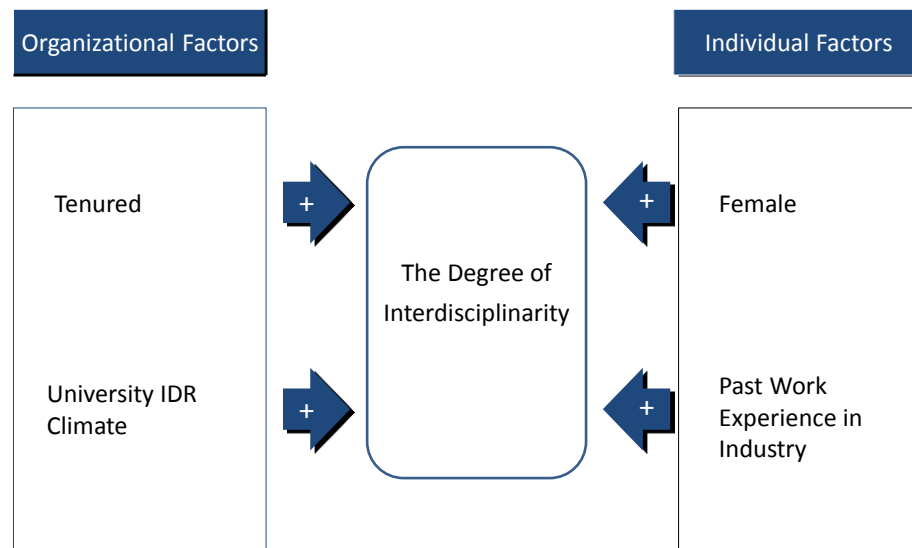


Figure 3 Factors Affecting Researchers' Interdisciplinarity

Two organizational level factors I identify are tenure system and university IDR climate. Tenure pressure is a crucial concern for young faculty and thus it is hypothesized that tenured faculty members are more likely to engage in research with a higher degree of interdisciplinarity than untenured. The climate for IDR at the university level, as an important dimension of organizational characteristics, is hypothesized to be positively related to individual level degree of interdisciplinarity, given that scientists could obtain more support and encouragement to engage in IDR in a favorable environment. Two individual factors discussed in this chapter are gender and previous industry experience. Female scientists, as an under-represented group in science, are likely to engage higher level of interdisciplinary activities because they may tend to avoid fierce competition in traditionally male-dominant fields. Past work experience in industry is seen as important S&T human capital embodied in individual scientists, which may have a positive impact on IDR, given that interdisciplinary activities are often oriented to industrial application.

CHAPTER 3: DATA, MEASURES AND METHODS

3.1 Data

“Bibliometric indicators only monitor one of the possible dimensions of interdisciplinarity: that reflected in journals through scientific communication practices. Since interdisciplinarity is a multidimensional concept, which refers not only to the knowledge practices but also to the structures and behavior of the research groups, we believe that a combined use of bibliometrics with more traditional sociological tools, such as survey techniques, more adequately provides a comprehensive insight into the problem” (Sanz-Menendez, Bordons et al. 2001, p.48).

In choosing data to test the hypotheses developed in the second chapter, two basic conditions are considered. First, the data should capture scientists’ interdisciplinary activities. Second, the data should provide individual researchers’ personal and institutional information for examining the effects of various factors at the individual and institutional level on IDR. Given the two conditions, a combination of survey data and bibliometric data would be well suited for addressing the research questions described here.

Specifically, the primary data I choose to support this study are drawn from one of the largest national studies of social and collaborative networks of academic scientists - “*Netwise I²: Women in Science and Engineering: Network Access, Participation, and*

² Co-PI’s Dr. Julia Melkers and Dr. Eric Welch

Career Outcomes” (NETWISE 2006), funded by NSF (Grant # REC-0529642). It is particularly suitable for the study for two main reasons. First, this extensive national survey of U.S. academic scientists and engineers not only gathers detailed demographics and academic background information of survey respondents, but also asks them many questions about their research activities, some of which are specifically relevant to IDR. Second, NETWISE program collects and codes lifetime bibliometric data for survey respondents, which allows measuring scientists’ interdisciplinary activities in borrowing and boundary-crossing. Besides the survey data and bibliometric data from NETWISE, I also draw one institutional variable from NSF Survey of Earned Doctorates (SED), which will be described in the later section.

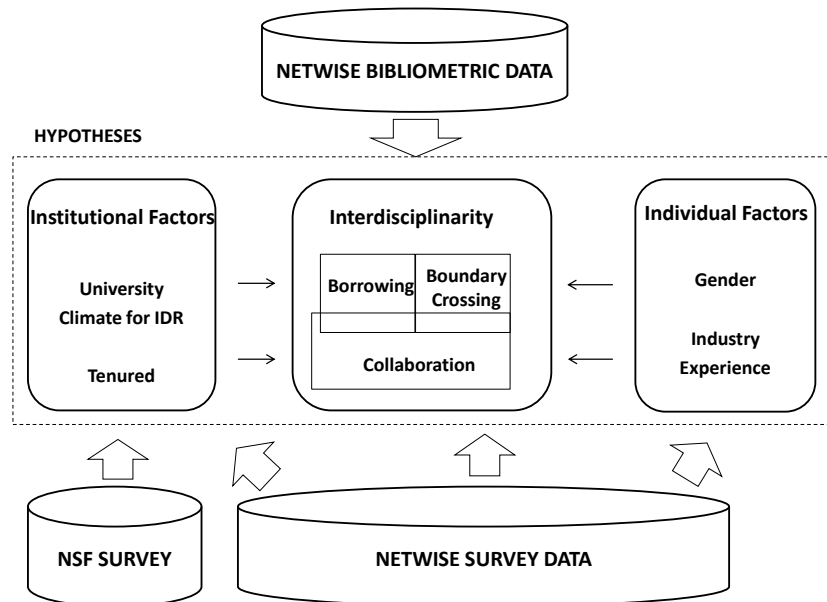


Figure 4 Three Datasets for Hypotheses Testing

3.1.1 NETWISE Survey Data

The data reported in this study comes from the first-stage survey of NETWISE, which was completed in March 2007. The first survey asked respondents about their research activities, including grant submission and success rate, teaching and committee responsibilities, attitudes towards and involvement in IDR, publications and the proportion of interdisciplinary publications, satisfaction with work-related resources, work environment, and detailed demographic and academic background questions. Another main part of the survey is it collects scientists' formal and informal network information through various name generator questions, which won't be used in this study although.

Our team conducted the survey using online survey software tools Sawtooth Software and provided each individual with a unique user-id and password to direct them to the website. People were invited to the survey via traditional mail and personal email, and reminded three times via email. One of the biggest advantages of online surveys is its flexibility in survey question design, because subsequent questions are often dependent on respondents' answers to prior questions. In our survey, for example, respondents were not further asked questions about their post-doc experience unless they had held a post-doc appointment.

The first-stage survey was drawn from the population of U.S. academic scientists and engineers in six disciplines (biological sciences, chemistry, computer science, earth and atmospheric sciences, electrical engineering, and physics) at 151 Carnegie-designated Research Extensive Universities. The selection of disciplines was based on the consideration of the different level of women's representation in distinct S&E fields,

in order to make comparisons between gender-balanced and male-dominated fields of study. The sample was stratified by rank, discipline and gender.

We sent survey invitations to 3,677 individuals and received 1,764 responses for a 50.1% response rate, of which 1,598 from 149 institutions were usable³. Responses were fairly evenly distributed across the six disciplines, gender (46% women) and rank (27% assistant professor, 28% associate professor, and 45% full professor⁴).

3.1.2 Bibliometric Data

Compared with other research methods, bibliometrics have several advantages: they enable large-scale evaluation of research activities; and they can provide comprehensive insights on various aspects of research activities because publications entail rich information. As an important component of NETWISE program, bibliometric data were gathered for the 1598 survey respondents from Thomson Reuters Web of Science (WoS) in 2007 and in 2010.

3.1.3 An Overview of WoS

We chose WoS for bibliometric data collection for two main reasons. First, WoS is one of the most popular and comprehensive citation databases for academic researchers, librarians, and research scientists. It covers over 12,000 top journals across more than 250 disciplines in areas of the natural sciences, social sciences, and arts and humanities. In the natural sciences, specifically, 8,058 journals are covered in WoS as of

³ Data were cleaned for incomplete responses. In the cleaning, no responses due to bad addresses were also removed for the calculation of response rate. For example, 136 of the emails were “bounced back” due to a bad email address and 19 were “returned to sender” by the recipient universities email server. Follow-up calls were made but respondents could not be located in these cases.

⁴ Emeritus and research scientists were not included in the sample.

April 1, 2010. These journals passed the strict evaluation by Thomson Reuters editors. They are the highest ranked journals and have the highest impact in their own fields. Second, all of our survey respondents are faculty members at Research Extensive Universities. They are top academic scientists and engineers in their fields of study. We believe that almost all of their publications would appear in prestigious journals which are most likely to be covered by WoS. Therefore, the coverage of WoS is appropriate for collecting bibliometric data for our survey respondents.

Moreover, the concept of subject category (SC) of WoS also provides a basis for measuring the degree of IDR (the indicators will be discussed in later sections). In the measurement of interdisciplinarity, the main challenge lies in how to define a field or discipline of science. In its system, WoS categorizes research areas into 244 SCs corresponding to disciplines. Each journal is assigned up to 6 SCs. For example, the journal *Molecular Biology of the Cell* is associated with one SC *Cell Biology*. Morillo, Bordens et al. (2003, p.1238 - 1239) mentioned three main advantages of the classification of journals into SCs: first, “it covers all fields of knowledge;” second, it is based on a regular “review of the journals content, as well as on the analysis of emergent patterns in cited/citing journals;” third, SCs are updated frequently.

3.1.4 Steps for Collecting Bibliometric Data

To gather bibliometric data for all survey respondents, our team took three main steps and followed detailed search protocol. First, we performed search on WoS, downloaded search results, and imported them to the software VantagePoint [www.theVantagePoint.com]. Based on every individual respondent’s curriculum vitae or university website information (if curriculum vitae was not available), we retrieved his

full name, listed all educational and professional institutions he has been affiliated, and recorded the year he received his Ph.D. degree. When performing searches, we applied two conditions: researcher's name and his publication starting year. To make sure our search results cover all papers with a respondent's name, we selected two name variations (surname plus first initial, and surname plus first initial plus middle initial). Meanwhile, to cover all papers in a researcher's career life, we subtracted 6 years from the year he received his Ph.D. degree⁵, and used the resulting year as publication start year for searching. Then we narrowed search results by checking all institutions that appear on the respondent's CV or website. Before we finally downloaded the refined search results, we did a rough check by eyeballing the publications on the CV and the search results to make sure there were no big discrepancies between them.

The initial dataset includes 81,796 articles published in five publication types (articles, reviews, proceedings papers, notes and letters) for 1589 researchers. We imported the data to the VantagePoint for the convenience of the following data processing, cleaning and analysis.

The second step is to ascertain the correct match of each paper with survey respondent, we constructed a small dataset of 4,253 articles published by a random sample of 100 survey respondents, and manually checked whether each paper does belong to the person in the survey. We estimated the error rate is about 8% and found that errors frequently take place in the situation of very common English and Asian last names.

⁵ We assumed that the earliest possible publication year for academic scientists would be 6 years earlier than they received their doctoral degrees.

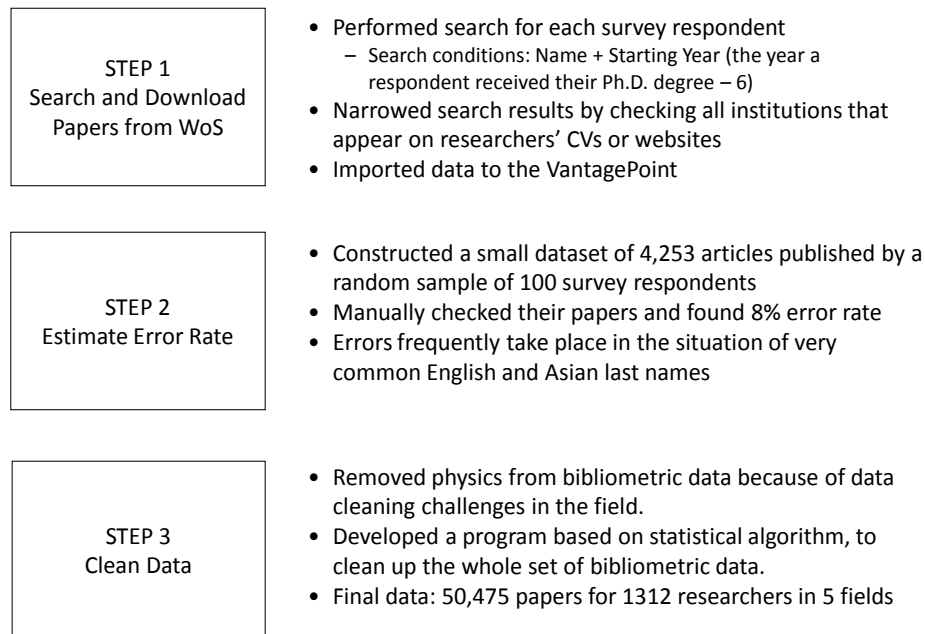


Figure 5 Three Steps for Collecting and Cleaning Bibliometric Data

The third step is to improve the accuracy rate of our bibliometric data. Two members of our team developed a program, based on a statistical algorithm, to clean up the whole set of bibliometric data (Wang, Berzins et al. 2012). The basic idea is that all papers of an individual should be highly correlated with each other in terms of names of all authors, cited journals, combined keywords, title words, abstract words, and SC; if any paper's correlation value is much lower than other papers of the same person, then this paper is probably a wrong one which does not belong to the person, and should be removed from our bibliometric data. The cosine similarity matrices were constructed for all papers under each respondent name. During the data cleaning process, we found that physicists' papers are very difficult to clean, because there are a large number of physics

papers with over 100 coauthors. To ensure the accuracy rate of the bibliometric data, we decided to exclude all physicists' papers from the final dataset.

The final bibliometric data include 50,475 papers for 1312 researchers. The average productivity is 38.5 per person. The publication year ranges from 1965 to 2010. In this study, however, I do not use the whole bibliometric data, but choose to create a subset of bibliometric data ranging from 2003 to 2007 so that bibliometric data are consistent with survey data in time period⁶. The subset bibliometric data include 13,809 papers for 1238 researchers.

3.2 Measures of Interdisciplinarity

For addressing what individual and organizational factors affect scientists' interdisciplinarity, the biggest challenge lies in how to measure the key dependent variable "interdisciplinarity." Ideally, the best index of the degree of IDR should be able to measure the overall degree to which scientists engage in all types of interdisciplinary activities. In reality, however, limited by research techniques and data availability, most scholars develop only one indicator to measure one dimension of IDR. Only a few scholars adopt multiple indicators to measure distinct interdisciplinary dimensions respectively, but they rarely combine these indicators into a single index to measure the overall degree of IDR, because there are many challenges such as scale inconsistency.

⁶ When the survey was conducted in 2007, respondents were asked to estimate the percentage of their interdisciplinary publications over the past five academic years.

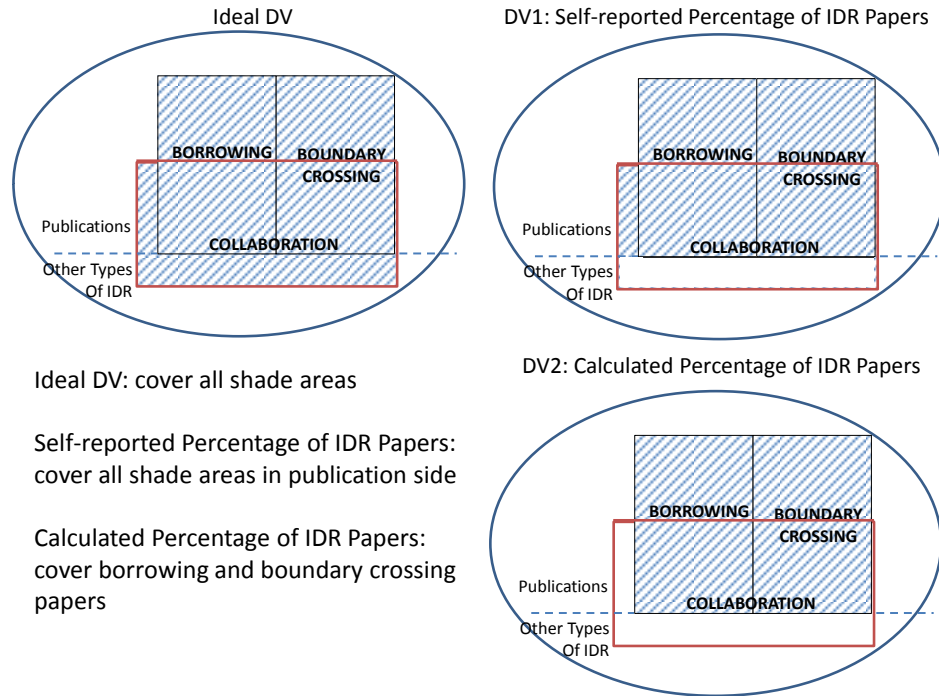


Figure 6 DVs Measuring the Overall Degree of IDR

This study encounters the same situation. The conceptual model of IDR introduced in chapter 2 has identified three main types of IDR: borrowing, boundary crossing and collaboration. If the circle represents all research activities one scientist engage in and the shade area represents IDR, then an ideal dependent variable of IDR should cover all information which borrowing, boundary crossing and collaboration convey, as shown in the upper-left of Figure 6. But it is very difficult to generate such an ideal index to measure the overall degree to which scientists engage in all types of interdisciplinary activities. Given that borrowing and boundary crossing both measure production aspects of IDR and coauthoring aspect of collaboration also has a large overlap with borrowing and boundary crossing in production outcomes, my measure of IDR in this study will focus on scientists' productions (borrowing and boundary crossing)

rather than the social aspects of collaboration. In particular, the index of IDR degree I use in the research is the percentage of IDR papers. Two variables based on survey data and bibliometric data, respectively, are created to measure this index.

3.2.1 DV1: Self-Reported Percentage of IDR Papers

The first variable is the percentage of IDR papers reported by scientists themselves. In the survey, respondents were asked “over the past five academic years, approximately what percentage of your overall publications would others in your discipline recognize as interdisciplinary?” Because the survey does not give a clear definition about what interdisciplinary means, respondents probably estimated the percentage based on their general understanding of IDR. Therefore, the papers they see as IDR papers could be those published outside scientists’ fields, or published within scientists’ own fields but borrowing much knowledge from distinct disciplines, or coauthored by members in distinct disciplines, or even some that the conceptual model of IDR does not cover. Conceptually, this variable is a sum of all interdisciplinary paper. Its measure of IDR should cover all IDR publishing activities, occupying all shade areas at the publication side, shown in the upper-right graph of Figure 6.

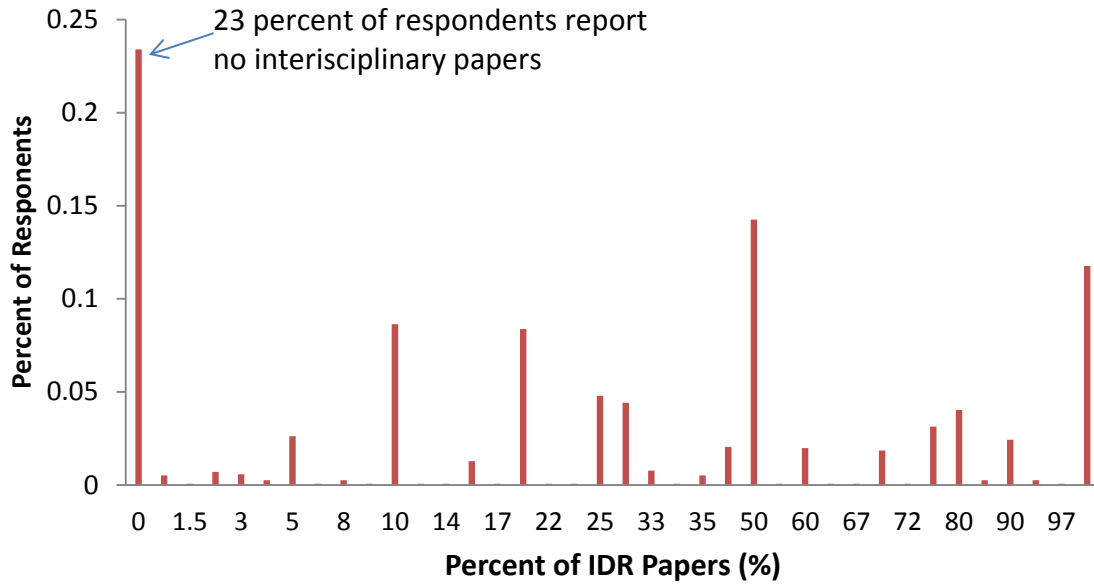


Figure 7 Distribution of the Percentage of Interdisciplinary Papers

However, there are two problems with the variable. First, it is a self-reported estimate of the overall degree to which scientists engage in publishing interdisciplinary papers. In some cases where respondents do not take the survey seriously or are not very good at evaluating their research, the indicator may be not very reliable. Also, the responses show that most of people tend to name an easily estimated number such as 10%, 50% or 80%, shown in Figure 7. To a great extent, therefore, this self-reported percentage does not represent the real percentage of interdisciplinary papers, but a rough estimate of their IDR publications. Second, respondents' own understanding of what can be counted as IDR papers may be different from what the conceptual model defines in this study. From the perspective, the variable may not accurately measure interdisciplinary publishing activities captured by the study.

Table 1 Descriptive Statistics of Self-Reported Percentage of IDR Papers

Discipline	# of Researchers	Mean	Standard Deviation	Min	Max
Full sample	1564	.37	.35	0	1
Sample without Physics	1300	.38	.35	0	1
Earth Science	285	.45	.34	0	1
Electrical engineering	206	.41	.34	0	1
Chemistry	281	.45	.37	0	1
Biology	271	.32	.33	0	1
Computer Science	257	.29	.32	0	1
Physics	264	.28	.34	0	1

3.2.2 DV2: Calculated Percentage of IDR Papers

At the same time, this study also calculates the percentage of IDR papers based on bibliometric data. The basic idea is that because borrowing and boundary crossing characterize interdisciplinary scientists' publishing activities within their own disciplines and in other disciplines, combining these two can provide a rough estimate for the overall IDR degree of scientists' production outputs (see the lower-right graph in Figure 6). In this study, my approach to calculate the percentage of IDR papers has two steps. The first step is to develop bibliometric indicators to measure borrowing and boundary crossing, respectively. The second step is to combine them to calculate the total percentage of IDR papers.

Borrowing - IDR Score

Bibliometric methods have already been widely applied in measuring IDR, because they are able to “produce a sufficiently detailed description of links between

subject fields to allow a search for, identification of, and analysis of important structural features” (Tijssen 1992, p.27). Drawing upon knowledge in different disciplines is often reflected in interdisciplinary scientists’ publications. For instance, nanotechnology is known as an emerging interdisciplinary area which covers the interface between physics, chemistry, biology, engineering, information technology, metrology, and other fields⁷. Using citation analysis, Bassecoulard, Lelu et al. (2007) found that nanoscience literature entails various disciplinary contents including engineering, medicine, biotechnology, chemistry, and physics.

The common bibliometric approach of measuring IDR is to take papers as the unit of analysis, and to measure how interdisciplinary one paper is on the basis of analysis of the co-occurrences of discipline-specific items (Schummer 2004). The underlying assumption is that when items representing different disciplines occur in the same paper, it means that the paper is interdisciplinary to some degree because of involving multiple disciplines. The discipline-specific items could be keywords (Rip and Courtial 1984, Morillo, Bordons et al. 2001), classification headings (Tijssen 1992), authors’ affiliations (Qin, Lancaster et al. 1997, Steele and Stier 2000, Schummer 2004), or citations (Porter and Chubin 1985, Tomov and Mutafov 1996). In co-author analyses, for instance, the co-occurrences of disciplinary affiliations of co-authors in a paper show an interdisciplinary relation among the disciplines of co-authors.

Likewise, this study adopts reference analysis to measure researchers’ borrowing knowledge from other disciplines. The idea is by measuring how many disciplines the

⁷National Nanotechnology Initiative. www.nano.gov/html/edu/home_edu.html

references cover and how different these disciplines are, one can assess the degree of the diversity of disciplines from which interdisciplinary researchers borrow knowledge. The bibliometric indicator was introduced by Porter and Rafols (2009). Here I call it the “IDR Score”.

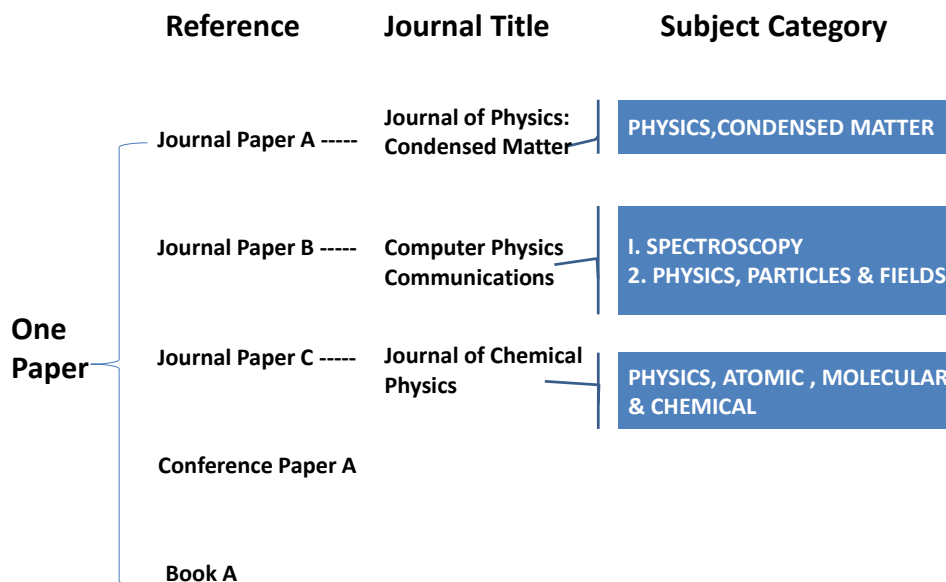


Figure 8 A Simple Example of the Structure of a Paper in WoS

The calculation of IDR score relies mainly on the concept of SC in WoS (See 3.1.3). Most published papers have several references: some of them are journal articles, some are conference papers, and some are books. Because WoS assigns SCs to each journal, one can collect a list of SCs with which a paper’s all cited journal papers are associated. In the example of Figure 8, for instance, the paper has four cited SCs shown on the right. In my subset bibliometric data, cited journal articles are associated with

total 234 SCs (which is called “cited SCs” in this approach). The range for individual SCs stretched from only 1 cite of journal articles associated with “criminology & penology” to 57,238 cites associated with “Biochemistry and Molecular Biology”.

The degree of difference between SCs is measured by a cosine value, which is based on a US national co-citation analysis of a sample of 30,261 papers during 2005-2007 from WoS. As Figure 9 shows, for example, the cosine value between SC *Biophysics* and SC *Biology* is .74, which is much higher than the cosine value between SC *Communication* and SC *Biology*. This means that Biology is more similar to Biophysics than to Communication.

Paper A – 5 Journal References		Paper B – 5 Journal References	
Subject Category	# Instances of SC appearing in the Paper’s References	Subject Category	# Instances of SC appearing in the Paper’s References
Biophysics	3	Communication	3
Biology	4	Biology	4

Cosine Value	Biophysics	Biology	Communication
Biophysics	1	0.738407	0.001839
Biology	0.738407	1	0.007074
Communication	0.001839	0.007074	1

$$I = 1 - \sum_{i,j} (S_{ij} P_i P_j)$$

IDR Score of Paper A < IDR Score of Paper B

Figure 9 A Simple Example of Comparison of Two Papers’ IDR Scores

The key characteristics of the IDR score are that “it captures not only the number of disciplines cited by a paper... but also how disparate (i.e. how different) these disciplines are” (Porter and Rafols 2009, p.3). The discipline-specific item this approach uses is journals research papers cite. Each cited journal is associated with one or more SCs in the WoS. Different WoS SCs represent different knowledge resources papers use. How many SCs one researcher’s articles cite and how disparate these SCs at a given time are together reflect the degree of interdisciplinarity of a person’s work during that period. Porter and Rafols generated the following formula for the IDR Score:

$$I = 1 - \sum_{ij} (S_{ij}P_iP_j)$$

Where P_i is the proportion of references citing the Subject Category SC_i in a given paper, and S_{ij} is the cosine measure of similarity between SC_i and SC_j . The higher one paper’s IDR score is, the more different research resources this paper borrows, the more diverse knowledge the authors use. If one paper cites references which are all associated with a single SC, or it cites references which are associated with two SCs that are extremely close, the paper has an IDR score of 0 or very close to 0.

In this study, one researcher’s borrowing activity is measured by his IDR Score, which is computed by averaging the IDR scores of all his papers published in his own discipline between 2003 and 2007, because borrowing means researchers borrow knowledge from other disciplines and then import it into their own disciplines. How to differentiate papers published in one researcher’s own discipline and published in other disciplines will be discussed in the next section.

Table 2 Descriptive Statistics of IDR Scores

Discipline	# of Researchers	Mean	Standard Deviation	Min	Max
Full sample	1193	.38	.13	0	.82
Earth Science	268	.42	.13	0	.82
Electrical engineering	183	.39	.15	.05	.81
Chemistry	259	.39	.12	.12	.70
Biology	254	.37	.11	.08	.67
Computer Science	229	.35	.14	0	.68

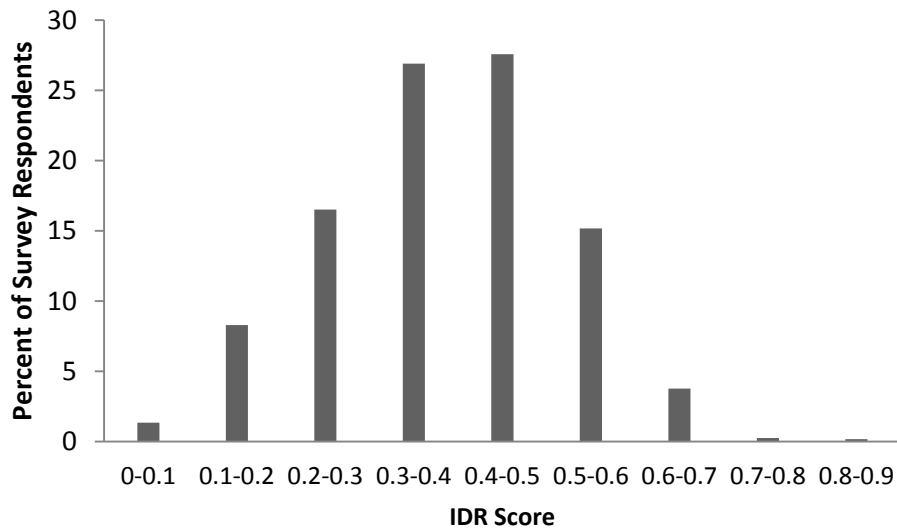


Figure 10 Distribution of IDR Score for the Sample of Scientists

Table 2 and Figure 10 present the descriptive statistics of IDR score in the sample⁸. The average score is 0.38. IDR scores for over 50% of scientists fall between 0.3 and 0.5, and only a few lower than 0.1 or higher than 0.7.

⁸ Physics is excluded because bibliometric data do not cover physics.

Boundary Crossing - Percentage of Papers published in other disciplines

Boundary crossing means interdisciplinary researchers publish work outside their own disciplines. In the study, the bibliometric indicator to measure boundary crossing is very straightforward. It is the percentage of papers published in other disciplines. Porter and his colleagues (Porter, Cohen et al. 2007) developed an indicator called “Specialization” to measure how many journal articles of one person are published in different SCs. Different from my indicator, specialization does not distinguish papers published in one’s own discipline and other disciplines.

Table 3 Categorization of Broad Publication Fields

Broad Publication Fields	Examples of SCs
BIOL	Genetics & Heredity; Ecology; Microbiology; Entomology; Plant Sciences; Physiology; Zoology
CHEM	Chemistry, Analytical; Polymer Science; electrochemistry; Chemistry, Organic; Chemistry, Inorganic & Nuclear; Crystallography
CS	Computer Science, Theory & Methods; Computer Science, Artificial Intelligence; Computer Science, Software Engineering
EAS	Oceanography; Environmental Sciences; Meteorology & Atmospheric Sciences; Geology; Paleontology; Geochemistry & Geophysics
EE	Engineering, Electrical & Electronic; Telecommunications; Engineering, Electrical & Electronic; Telecommunications
PHYS	Physics, Applied; Physics, Fluids & Plasmas; Spectroscopy; Astronomy & Astrophysics; Optics; Physics, Condensed Matter
OTHER	Ophthalmology; Nutrition & Dietetics; Psychology; Public, Environmental & Occupational Health; History & Philosophy Of Science

Table 4 One Example of Computing Percentage of Papers Published in Other Disciplines

Papers of One Respondent	Respondent Field	SCs associated with papers	Broad Publication Field	Published in other disciplines
Paper 1	EE	Chemistry, Organic	CHEM	Yes
Paper 2	EE	Chemistry, Analytical	CHEM	Yes
Paper 3	EE	Engineering, Electrical & Electronic; Engineering, Mechanical	EE	No
Paper 4	EE	Engineering, Electrical & Electronic; Engineering, Mechanical	EE	No
Paper 5	EE	Engineering, Electrical & Electronic; Engineering, Mechanical	EE	No

To compute the percentage of one’s papers published in other disciplines, the key work is to judge whether one publishes his papers within his discipline or in other disciplines. Survey respondents are from six disciplines, based on their department affiliations: Biology (BIOL), Physics (PHYS), Electrical Engineering (EE), Computer Science (CS), Earth Science (EAS), and Chemistry (CHEM). So I classify scientific disciplines into seven broad publication fields, including the above six fields and the seventh field “Other,” as shown in the first column of Table 3. In judging which field one paper belongs to, I borrow the categorization of SCs from WoS. First, all SCs are assigned to one of the seven broad publication fields (see Table 3). According to the categorization of SCs into broad publication fields, one can know to which publication field a paper belongs. Then I compare survey respondent field with their publication fields, and code whether papers were published within or outside respondent field.

Lastly, I compute the percentage of papers published in other disciplines. Table 4 illustrates one example. The researcher in EE has 5 papers between 2003 and 2007, of which 2 papers were published in the field of CHEM and 3 papers in his own field EE, shown in the fourth column. So the percentage of papers published in other disciplines for this person is 40%.

Table 5 Descriptive Statistics of Percentage of Publications in Other Disciplines

Discipline	# of Researchers	Mean	Standard Deviation	Min	Max
Full sample	1238	.17	.25	0	1
Earth Science	274	.14	.22	0	1
Electrical engineering	193	.23	.30	0	1
Chemistry	267	.22	.26	0	1
Biology	261	.15	.22	0	1
Computer Science	243	.14	.25	0	1

In the subset of bibliometric data used in the study, there are 13,809 papers published by 1238 survey respondents (physicists excluded) between 2003 and 2007. Among them, 2383 papers are published outside researchers' disciplines. Table 5 and Figure 11 present the descriptive statistics of this indicator in the sample. The average percentage of papers published in other disciplines for the sample of scientists is about 17%. Almost 90 percent of people published more than 50% of their papers in their own disciplines, and only a few scientists have high percentage of papers published in other

disciplines. Specifically, 49 percent published all of papers within their own disciplines between 2003 and 2007. They are the least “boundary crossing” people.

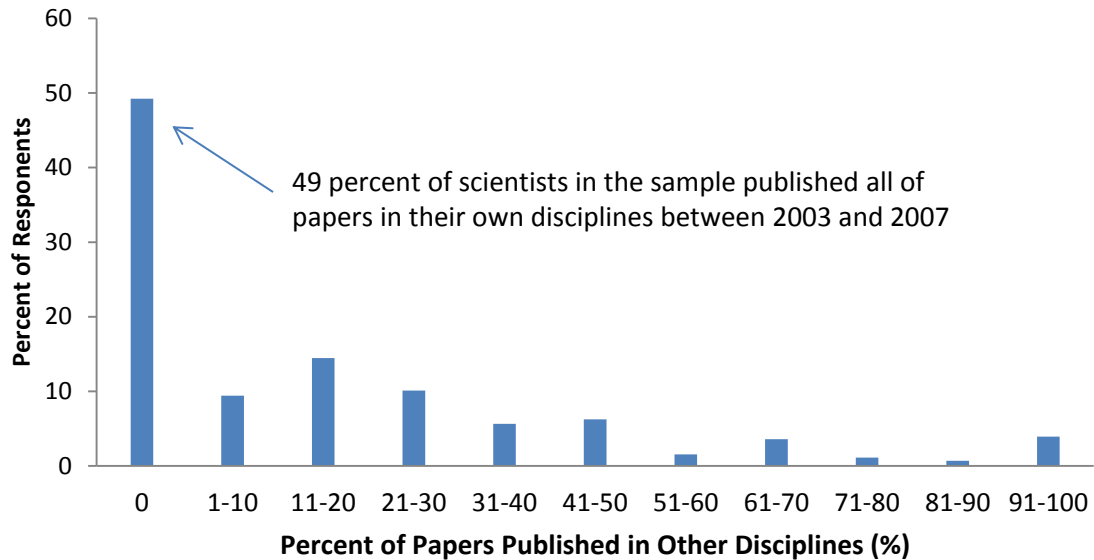


Figure 11 Distribution of the Percentage of Papers Published in Other Disciplines for the Sample of Scientists

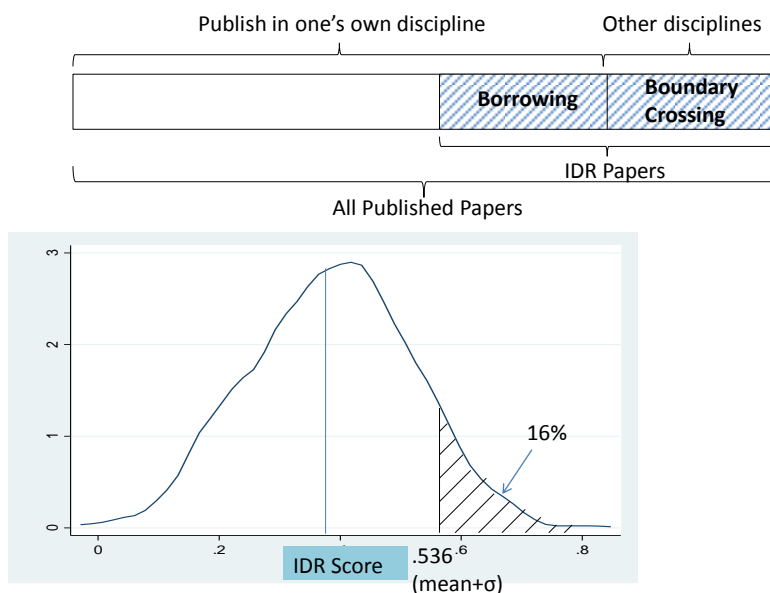
Combining borrowing and boundary crossing

After the two bibliometric indicators of borrowing and boundary crossing are generated, my next step is to combine them to calculate the percentage of IDR papers. Here, IDR papers include both “borrowing papers” and “boundary crossing papers.” So the percentage of one person’s IDR papers is calculated by combining the percentage of borrowing papers and the percentage of boundary crossing papers (which are those published outside scientists’ own disciplines):

Calculated Percentage of IDR Papers

$$= (\text{Total number of Borrowing Papers} + \text{Total number of Boundary Crossing Papers}) / \text{Total number of Papers}$$

$$= \text{Percentage of Borrowing Papers} + \text{Percentage of Boundary Crossing Papers}$$



- Borrowing Papers are papers published in one's own discipline and their IDR scores are higher than .536. (.536 is the sum of mean and standard deviation of IDR scores)
- Boundary Crossing papers are papers published in other disciplines.

Figure 12 The Composition of IDR Papers

Because the percentage of boundary crossing papers has already been coded earlier, the key work here is to identify borrowing papers, based on their IDR scores. IDR score is a continuous variable between 0 and 1. The more distinct disciplines from which a paper borrows knowledge, the higher IDR score it has. Hence, a paper with 0.6 IDR score is seen as being more interdisciplinary than one with 0.5 IDR score, from the borrowing perspective. But, the problem is to define borrowing papers,

what is the cut-off value of IDR score? Is a paper with IDR score higher than 0.5 a borrowing papers or the one higher than 0.6?

My approach is to set the cut-off value as the mean of IDR scores of the whole sample plus one standard deviation. As Figure 12 shows, the distribution of IDR score is very close to normal distribution. For the normal distribution, one standard deviation from the mean accounts for 68.27%. That is to say, if the cut-off IDR score is 0.536 (the sum of the mean of IDR scores and one standard deviation), then there are about 16% of papers published in researchers' own fields whose IDR scores are higher than 0.536. In this study, I call these papers "borrowing papers." After borrowing papers and boundary crossing papers are coded, I can calculate every researcher's percentage of IDR papers by dividing the total number of his borrowing papers and boundary crossing papers by the total number of his papers.

The biggest advantage of calculated percentage of IDR papers is that it captures two dimensions of IDR: borrowing and boundary crossing by combining the two bibliometric indicators, which makes it more powerful than other IDR indicators measuring only one dimension of IDR. But this variable has two big limitations. First, choosing the cut-off value for indentifying borrowing papers is somewhat arbitrary. Table 6 compares the calculated percentage of IDR papers with the self-reported percentage. It can be seen that for the full sample, the calculated percentage is a little bit lower than the self-reported percentage. It is reasonable, because conceptually, the self-reported percentage covers all types of IDR papers while the calculated percentage only includes borrowing and boundary crossing papers, as Figure 6 shows. However, when looking at the two percentages by discipline, we can find that if we use the self-reported

percentage as a benchmark and expect the calculated percentage is slightly lower than the self-reported, the calculated percentage may underestimate the degree to which earth scientists, chemists and biologists engage in publishing IDR papers, but overestimate computer scientists and electrical engineers. Second, the calculated percentage of IDR papers does not cover all interdisciplinary papers. There may be some IDR papers which do not fall into borrowing or boundary crossing. Hence, strictly speaking, the calculated percentage of IDR papers underestimates the overall degree of IDR.

Table 6 Descriptive Statistics of Calculated Percentage of IDR Papers

Discipline	Self-Reported Percentage of IDR Papers ⁹	Calculated Percentage of IDR Papers			
	Mean	Mean	SD	Min	Max
Full Sample without Physics	.38	.32	.33	0	1
Earth Science	.45	.34	.34	0	1
Electrical engineering	.41	.41	.36	0	1
Chemistry	.45	.34	.31	0	1
Biology	.32	.23	.27	0	1
Computer Science	.29	.32	.34	0	1

In a brief summary, I use two dependent variables in this study: one is self-reported percentage of IDR papers and the other is calculated percentage of IDR papers.

⁹ Standard deviation, min and max values of self-reported percentage of IDR papers are reported in Table 5. Table 6 only reports its mean value for the purpose of comparison.

Both of them measure the production aspects of IDR. So the common limitation is that they do not cover social aspects of collaboration.

3.3 Measures of Independent Variables

Corresponding to the four hypotheses developed in Chapter 2, there are four key independent variables, in which gender, professional industry experience, and tenure status¹⁰ are coded as dummy, straightforwardly based on survey questions.

Regarding the factor “university climate for IDR,” this study uses a proxy variable as its measure: the proportion of STEM doctorate recipients reporting interdisciplinary dissertation research fields at the university level between 2002 and 2006. As mentioned earlier, university climate for IDR actually means the overall perception and attitudes of the university towards IDR. Better climate for IDR on campus would be reflected in more university scientists who are in favor of and are willing to working on IDR. Hence, the higher proportion of interdisciplinary doctorate dissertations in a university means higher level of interdisciplinary climate on campus, because it synthesizes, at the aggregate, much information of university characteristics in encouraging and conducting IDR in an implicit way, such as institutional aspirations for IDR, institutional support for IDR, and the overall capacity of conducting complex scientific and engineering research at the institutional level.

¹⁰ Tenure is coded based on survey responses returned in 2007. The time period of bibliometric dataset I created for this study is 2003-2007. For all respondents reporting “untenured” in 2007, they should be in pre-tenure status when publishing between 2003 and 2007. For respondents reporting “tenured” in 2007, some of them may receive tenure during the period from 2003 to 2007. But I still treat these people as tenured, assuming that their behavior might be closer to tenured.

The NSF SED provides the indicator for this study. Since 2001 the SED has gathered information on new doctorate holders' primary and secondary fields of dissertation research (NSF 2010b). Specifically, it examined the proportion of all doctorate recipients who reported multiple dissertation research fields in each institution. In 2010, NSF's statistics report also listed top fifty schools with largest number of the SED respondents reporting interdisciplinary research fields in their website. All NETWISE survey respondents are from six S&E fields at 151 Research Extensive Universities. National Opinion Research Center provided us with institutional data on proportion of STEM doctorate recipients reporting interdisciplinary research fields for all research universities between 2002 and 2006, as our team requested.

Table 7 Descriptive Statistics of Independent Variables and Disciplines

Variable	Mean (%)	Standard Deviation	Min	Max
Tenured	69.5	.46	0	1
Male	54.3	.50	0	1
Having industrial experience	8.4	.28	0	1
University Climate for IDR (proportion of STEM doctorate recipients reporting interdisciplinary dissertation research fields)	28.2	5.12	12.5	46.6
Physics	17.2	.38	0	1
Chemistry	17.7	.38	0	1
Biology	17.4	.38	0	1
Earth Science	18.2	.39	0	1
Computer Science	16.3	.37	0	1
Electrical engineering	13.1	.34	0	1

Table 7 provides descriptive statistics for all independent variables, including means, standard deviation, minimum and maximum value. We can see that 70 percent of survey respondents have received tenure, 54 percent are male, 8 percent used to work in industry. The respondents are almost evenly distributed among the six disciplines.

3.4 Method

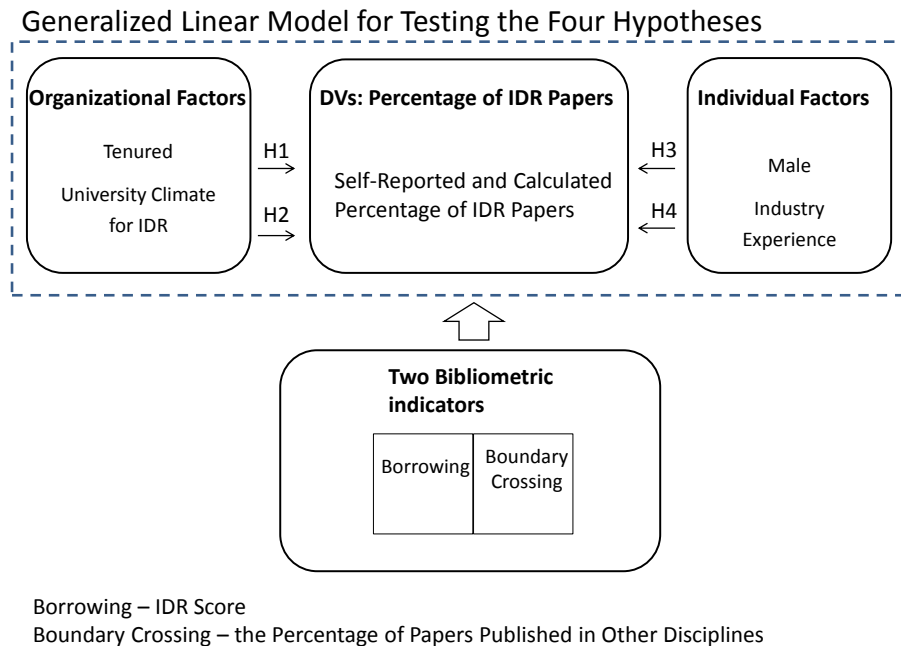


Figure 13 Four Hypotheses Tested by GLM

The primary questions of this study are what individual and institutional factors affect scientists' IDR and what the effects of these factors are in different disciplines. In Chapter 2, I identify tenure, university IDR climate, gender, and past work experience in industry are four key factors, and formulate hypotheses about their effects on the degree

of interdisciplinarity. To address the research questions and test the hypotheses, I will make descriptive and regression analyses of these factors and their effects on IDR.

3.4.1 Descriptive Analyses

First, I provide detailed descriptive analyses of the degree to which scientists in each discipline engage in borrowing and boundary crossing by investigating the two bibliometric indicators. As the conceptual model in Chapter 2 describes, borrowing and boundary crossing represent different ways of transferring knowledge, and they have different meanings. Discussing and comparing how scientists in distinct fields conduct IDR through different means can help characterize interdisciplinary activities of academic scientists in each discipline. Second, I discuss how the self-reported and calculated percentage of IDR papers differ by tenure status, gender, industrial work experience and discipline by conducting an analysis of variance (ANOVA). The bivariate analyses explore whether these independent variables have different effects on interdisciplinarity.

In addition, one thing worth mentioning here is that physics is a special case in this study, because bibliometric data do not cover physics, but survey data do. Given the uneven data, there are two options. The first is to still keep physics in analyses and the second is to remove it. I choose the first option because physics is a traditional discipline. Studying physicists' interdisciplinary activities and comparing them with scientists in other disciplines through investigating indicators only based on survey data still can provide insights into addressing research questions.

3.4.2 Regression Models

The second step is to build regression models to estimate the degree of interdisciplinarity in the full sample and each discipline. The two dependent variables - self-reported percentage of IDR papers and calculated percentage of IDR papers both are fractional variables bounded between 0 and 1. There are two considerations in choosing regression models for them. First, neither of them is normally distributed, which means that linear regression model is not suitable for them. Second, both of them have a lot of zeros and ones, as shown in Figure 14 and 15. Hence, it is not appropriate to perform a logarithmic transformation on them; otherwise the transformation would produce many missing values for the observations with value 0 and thus drop them from the sample. In order to circumvent these issues, I choose generalized linear model (GLM) with a logit link function and a binomial distribution (fractional logit model) to test the hypotheses. GLM is an approach developed by Papke and Wooldridge (1996). It is built on the Bernoulli quasi-likelihood method and is efficient for fractional dependent variables.

The basic function of a generalized linear model is

$$g[E(y)] = X\beta$$

where $g(\cdot)$ is the link function, β is the Quasi Maximum Likelihood Estimator (Gourieroux, Monfort et al. 1984), and X is the matrix of independent and control variables.

The link function represents the relationship between expected value of the dependent variable Y and $X\beta$. There are various forms of link function. For example, for standard linear models, the link function is $g(y) = y$. In this study, the link function I

choose for the two fractional dependent variables bounded between 0 and 1 is logit function. Its form is

$$Y = \frac{\exp(X\beta)}{1 + \exp(X\beta)}$$

The predicted value Y is in the range [0,1].

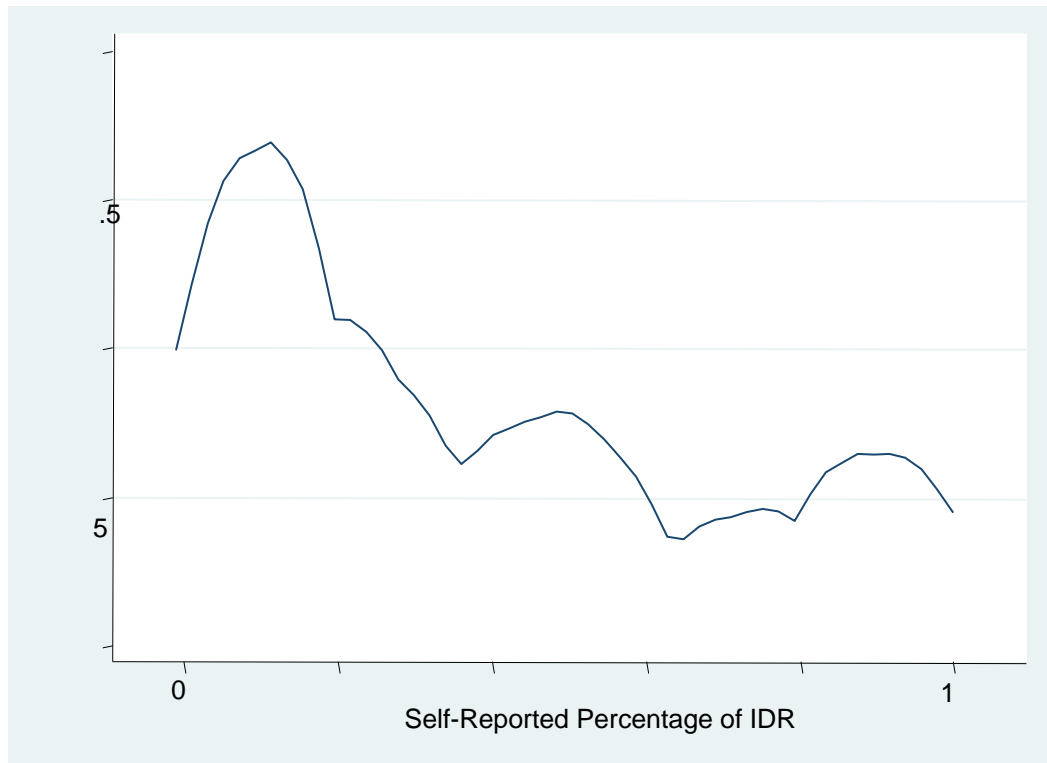


Figure 14 Density Distribution of Self-Reported Percentage of IDR Papers

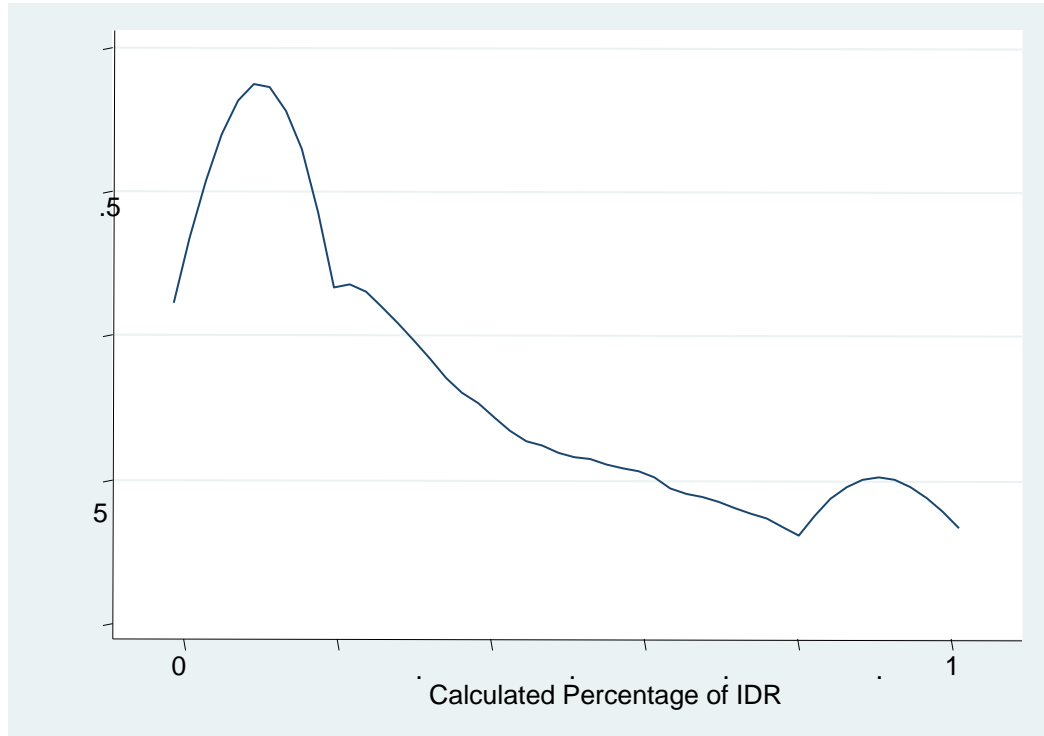


Figure 15 Density Distribution of Calculated Percentage of IDR Papers

CHAPTER 4: RESULTS AND FINDINGS

4.1 Descriptive Analyses

The descriptive analyses include four parts. First, I look at descriptive data of various independent variables. Understanding them would facilitate the following discussion of how the degree of interdisciplinarity is different in distinct groups. Second, I analyze and compare how scientists in distinct disciplines engage in borrowing and boundary crossing by investigating the two bibliometric indicators measuring them. Third, I discuss how the overall degree of IDR (the two dependent variables) differs by tenure status, gender, industrial work experience and discipline by conducting an analysis of variance (ANOVA). Lastly, I summarize the findings to characterize scientists' interdisciplinary activities in each discipline.

4.1.1 Descriptive Analysis of Independent Variables

In this study, four independent variables are tenure, university climate for IDR, gender, and past work experience. Figure 16 demonstrates faculty composition by tenure status and gender in the six disciplines. We can see no big differences between them. In the survey sample, 135 out of 1598 respondents have had industry experience. Figure 17 shows that two-thirds of them are in electrical engineering or computer science, indicating that career mobility between academia and industry is more likely to occur in applied S&E areas.

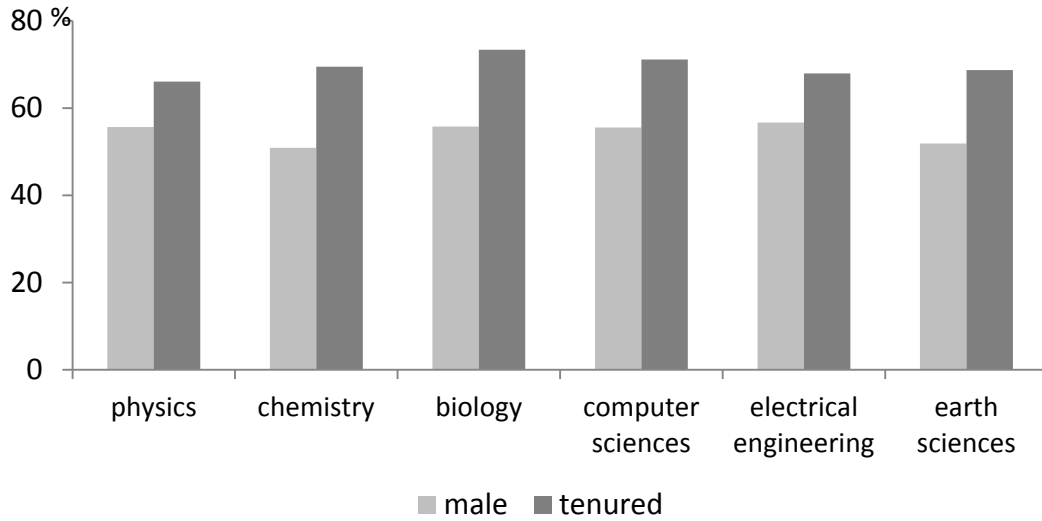


Figure 16 Faculty Composition by Tenure Status and Gender in Six Disciplines

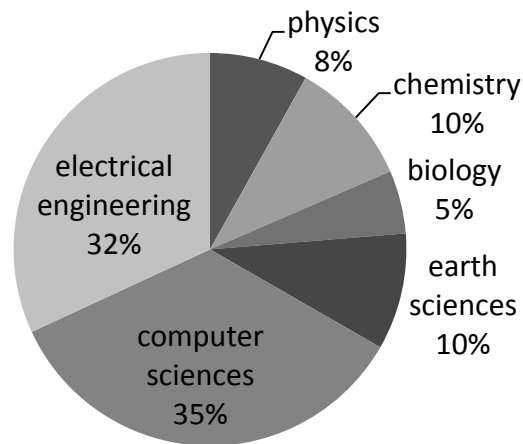


Figure 17 Distribution of Survey Respondents with Industry Experience by Discipline

University Climate for IDR is measured by the proportion of STEM doctorate recipients reporting interdisciplinary dissertations at the institutional level. Table 8 presents the distribution of this index. It can be seen that among the 149 universities included by NETWISE survey responses, 7 universities have more than 40% of STEM

doctorate holders who reported interdisciplinary dissertation research fields between 2002 and 2006, and 71 survey respondents are from these universities. About 45% of researchers in this study are from the institutions where with medium-level IDR climate (the proportion is between 25% and 29.9%).

Table 8 Distribution of the Index of University Climate for IDR

University Climate for IDR	Institutions	Individual Survey Respondents	
		N	Percent (%)
Range of Proportion of STEM Doctorate Recipients Reporting Interdisciplinary Dissertation Research Fields in 2002-06	N	N	Percent (%)
12.5-19.9%	6	37	2.3
20-24.9%	32	362	22.7
25-29.9%	57	711	44.5
30-34.9%	30	305	19.1
35-39.9%	17	112	7.0
40-46.6%	7	71	4.4
Total	149	1598	100

4.1.2 Descriptive Analysis of Borrowing and Boundary Crossing

Comparison of Two Bibliometric Indicators

This section focuses on discussing the degree to which scientists in each discipline engage in borrowing and boundary crossing. To do so, it first compares the meaning, pros and cons of the two bibliometric indicators measuring borrowing and boundary crossing, shown in Table 9. It can be seen that they measure different interdisciplinary aspects of scientists' production outputs. The correlation value between

the two indicators is .28, showing that they are not highly correlated with each other. For example, scientists in some interdisciplinary fields conduct IDR through borrowing theories and methods from other disciplines. They publish interdisciplinary papers in journals within their own fields, and seldom in other disciplines. In these cases, the IDR scores for the scientists are high but the percentages of papers in other disciplines are very low. Moreover, it implies that measuring the overall degree of IDR cannot rely on one single indicator.

Table 9 Comparison of Two Bibliometric Indicators

	Borrowing – IDR score of papers published in scientists’ own disciplines	Boundary Crossing – Percentage of papers published in other disciplines
Meaning	Measuring borrowing – how many different disciplines scientists’ references cover and how diverse these disciplines are.	Measuring boundary crossing – the percent of papers published in other disciplines.
Pros	It depends on the SC classification of WoS and is based on the diversity index calculation formula, less dependent on human opinion.	The formula of computing this indicator is operationally simple. Its meaning is understandable and interpreted easily.
Cons	There exists error rate with publication data collection. The indicator is largely relied on the correlation matrix between SCs which is calculated based on co-citation analysis of a sample. But the sample does not completely match the scientific fields the survey covers.	There exists error rate with publication data collection. The classification of publication fields is broad. And it is difficult to assign a field to journals which are interdisciplinary themselves or associated with multiple SCs.

Statistical Analysis of Borrowing and Boundary Crossing in Each Discipline

Table 10 shows the degrees to which scientists in each discipline engage in borrowing and boundary crossing. First, it can be seen that in our survey sample, earth scientists have the highest average IDR score, indicating that they have the most diverse references in their papers published in their own earth science fields. In other words, earth scientists like to cite references from other different disciplines the most. Second to earth scientists, researchers in chemistry and electrical engineering also have high average IDR score. The lowest average IDR score is in the field of computer science. Second, scientists in electrical engineering are the most “boundary crossing” group. On average, electrical engineers publish 23% of their papers in other disciplines. The least “boundary crossing” are computer scientists and earth scientists whose average percentages of papers published in other disciplines are both 14%, slightly lower than biologists who publish 15% of papers outside biology.

Table 10 Borrowing and Boundary Crossing of Scientists in Each Discipline

	CHEM	BIOL	CS	EE	EAS
Borrowing (IDR score of papers published in scientists’ own disciplines)	.39	.37	.35	.39	.42
Boundary Crossing (percentage of papers published in other disciplines)	.22	.15	.14	.23	.14

Table 11 makes a detailed comparison of IDR score between different groups in each field, and reports the results of ANOVA analysis. First, the average IDR score of female scientists in the full sample is significantly higher than male scientists at the 0.1

level. Specifically, female computer scientists have significantly higher IDR scores than their male counterparts. This means that female faculty in computer science cites more references from diverse disciplines in their papers published in computer science, showing that female computer scientists may be more interdisciplinary in borrowing information and knowledge from other disciplines. Regarding gender difference, the other interesting finding is that biology is the only discipline in which male scientists have average higher IDR score than female, but the difference is not significant.

Table 11 Comparison of IDR Score between Groups

		COMBINED	CHEM	BIOL	CS	EE	EAS
Gender	Male	.379	.389	.374	.331	.387	.410
	Female	.392	.396	.357	.382	.394	.426
	Difference	*			***		
Tenure Status	Tenured	.384	.394	.376	.356	.387	.406
	Untenured	.386	.388	.335	.349	.400	.445
	Difference			**			**
Industry	With industry experience	.384	.463	.332	.356	.389	.415
	Without industry experience	.385	.389	.367	.354	.390	.418
	Difference		**				

Notes: * p<0.10; ** p<0.05; *** p<0.01; **** p<0.001; the sample size drops for the full model.

Second, although there is no statistically significant difference in IDR score between tenured and untenured groups for the full sample, we can see significant differences between tenured and untenured people in earth science and biology. Table 10

has shown that earth scientists have the highest average IDR score and they are the most “borrowing” group. In earth science, we can find that untenured scientists have significantly higher IDR score than tenured, showing that my tenure hypothesis may not be true in earth science. However, in align with my hypothesis, the average IDR score of tenured biologists is .38, which is significantly higher than untenured biologists. Third, chemistry is the only discipline in which faculty with industry experience has significantly higher IDR score than those without industry experience.

Table 12 Comparison of Percentage of Papers Publish in Other Disciplines between Groups

		COMBINED	CHEM	BIOL	CS	EE	EAS
Gender	Male	.157	.182	.152	.122	.216	.126
	Female	.191	.252	.141	.162	.259	.154
	Difference	**			***		
Tenure Status	Tenured	.158	.187	.136	.135	.222	.130
	Untenured	.206	.278	.183	.152	.261	.161
	Difference			**			**
Industry	With industry experience	.226	.262	.235	.186	.292	.100
	Without industry experience	.167	.214	.145	.130	.220	.141
	Difference		**				

Notes: * p<0.10; ** p<0.05; *** p<0.01; **** p<0.001; the sample size drops for the full model.

Likewise, Table 12 compares the average percentage of papers published in other disciplines between different groups. The results are almost consistent with Table 11.

For example, female scientists in the full sample and computer science publish

significantly higher percentage of papers outside their own disciplines than male in the full sample and computer science, respectively. Again, biology is the only discipline where male faculty has higher percentage of papers published outside biology than female, and chemistry is the only discipline where the difference between scientists with industry experience and those without the experience is significant. Comparing the two tables, we can find that the only difference is in tenured and untenured biologist groups. Table 11 shows that tenured biologists are stronger in borrowing than untenured, while Table 12 tells us that untenured are stronger in boundary crossing. The finding further shows that borrowing and boundary crossing may not be highly correlated.

4.1.3 Descriptive Analysis of Dependent Variables

After discussing the different degrees to which scientists in distinct fields engage in borrowing and boundary crossing, I will analyze the overall degree of interdisciplinarity for scientists in each discipline in this section.

There are two dependent variables in this study: self-reported percentage of IDR papers and calculated percentage of IDR papers. The correlation value between the two percentages is 0.35, showing they are not very highly correlated with each other. There are two possible reasons. First, conceptually, although both of them are used to measure the overall degree to which scientists engage in publishing IDR papers, the self-reported percentage is based on scientists' own estimate. Their understanding of IDR may be different from the conceptual model in this study. Hence, the papers they count as IDR papers in the survey may or may not include borrowing and boundary crossing papers defined in calculated percentage. From this perspective, the two measures have a large

overlap but they do not measure the same thing. Second, there are measurement errors with both of them. Their limitations were discussed in the previous chapter.

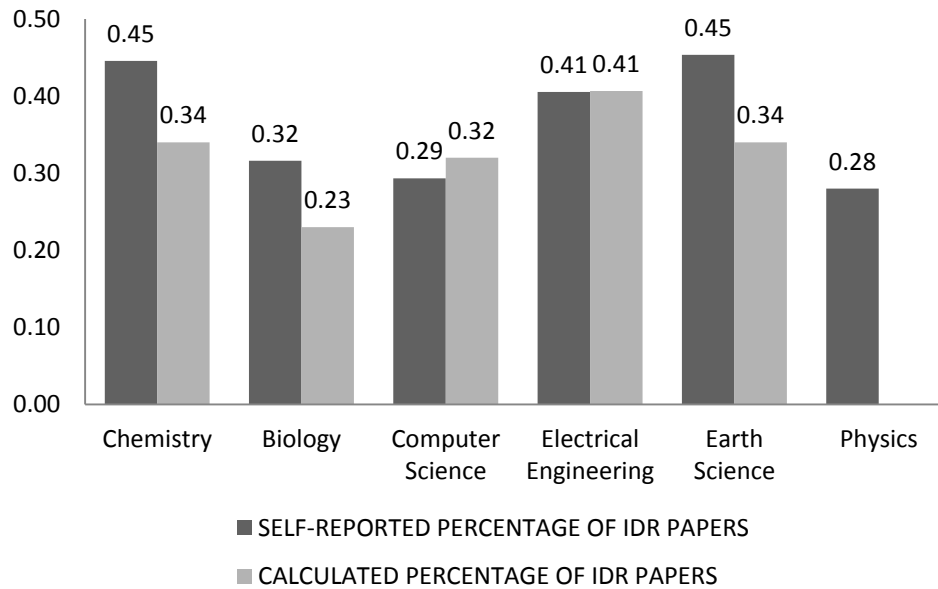


Figure 18 Self-Reported and Calculated Percentages of IDR Papers by Discipline

Figure 18 demonstrates the average values of the two dependent variables in each discipline. Although calculated percentage of IDR papers is not available for physics, we still can see that physicists report the lowest percentage of IDR papers in our survey, showing that physics is the least interdisciplinary. Top three interdisciplinary disciplines are chemistry, electrical engineering and earth science. Earth scientists and chemists report the average highest percentage of IDR papers, while the calculate percentages of IDR papers for these two disciplines are 34%, lower than their reported values. If we use the reported percentage as a benchmark, the calculated percentage may underestimate the overall degree of IDR of chemists and earth scientists. Probably it is because the cut-off

value of IDR score I define to identify borrowing papers is a little bit high for the two disciplines. The range of the calculated percentage of IDR papers depends largely on the cut-off value of IDR score. The higher the cut-off value, the fewer the number of borrowing papers, the lower percentage of IDR papers. Consistent with the earlier discussion, biology and computer science are two disciplines with low IDR degree. In our survey, biologists and computer scientists reported average 32% and 29% of their papers recognized as IDR, respectively, which are slightly higher than physicists, but much lower than scientists in chemistry, earth science and electrical engineering. The calculated percentages based on bibliometric data are 23% and 32% for them, which are also the two lowest values among the disciplines except physics.

Table 13 Five Categories of Scientists Based on Their Degree of IDR

Group Type	Cut-off Values of Percentage of IDR Papers	Self-Reported ¹¹		Calculated	
		N	Percent (%)	N	Percent (%)
G1: Scientists with very low IDR	< 20%	459	40.2	577	46.7
G2: Scientists with low IDR	Between 20% and 40%	263	23.0	231	18.7
G3: Scientists with medium IDR	Between 40.1% and 60%	222	19.4	144	14.3
G4: Scientists with high IDR	Between 60.1% and 80%	102	8.9	118	11.2
G5: Scientists with very high IDR	> 80%	96	8.4	165	14.8

¹¹ Physics is not included in the table for the convenience of comparison between the two percentages

In order to better understand how the two percentages of IDR papers are distributed in each discipline, I classify scientists of the sample into five groups. Researchers having very close to 0 percent, 50 percent, and 100 percent of IDR papers are labelled as very low IDR (group 1), medium IDR (group 3), and very high IDR people (group 5), respectively. Between group 1 and 3 is low IDR people (group 2), and between group 3 and 5 is high IDR people (group 4).

Table 13 shows the distribution of scientists of the survey sample in the five groups, based on their self-reported and calculated percentages of IDR papers. We can see that overall, my calculation shows more scientists in the two extreme groups (very low or very high IDR) than the reported data from the survey. Two reasons may explain it. One is when scientists estimate the percentage of their IDR papers, they may tend to be not very aggressive. For example, even if one person's papers are all boundary crossing papers with high IDR scores, he may report that 75% of his papers are recognized as interdisciplinary and thus he falls into group 4. But my calculation will label him as group 5. The other reason is that the calculated percentage of IDR papers is based on publication data, and papers written by the same person often have some common characteristics (e.g., very similar references or journals). Then papers with the same author are very likely to be labeled as the same type: borrowing or non-borrowing, boundary-crossing or non boundary-crossing. This is likely to lead to either a very low or very high percentage of IDR papers. As a result, we can find that more scientists are in the two extreme groups based on calculated percentage of IDR papers.

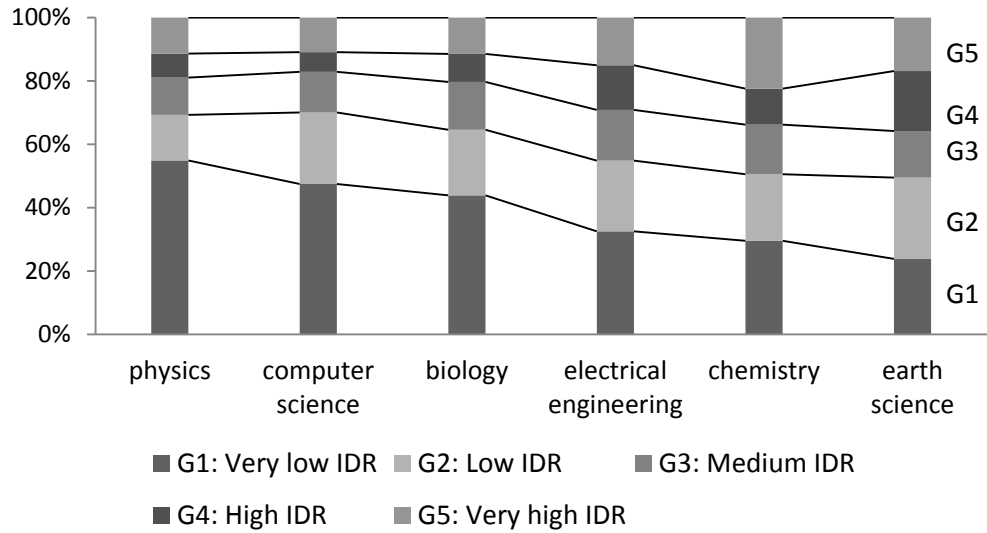


Figure 19 Distribution of Five Groups Classified Based on Self-Reported Percentage of IDR Papers in Each Discipline

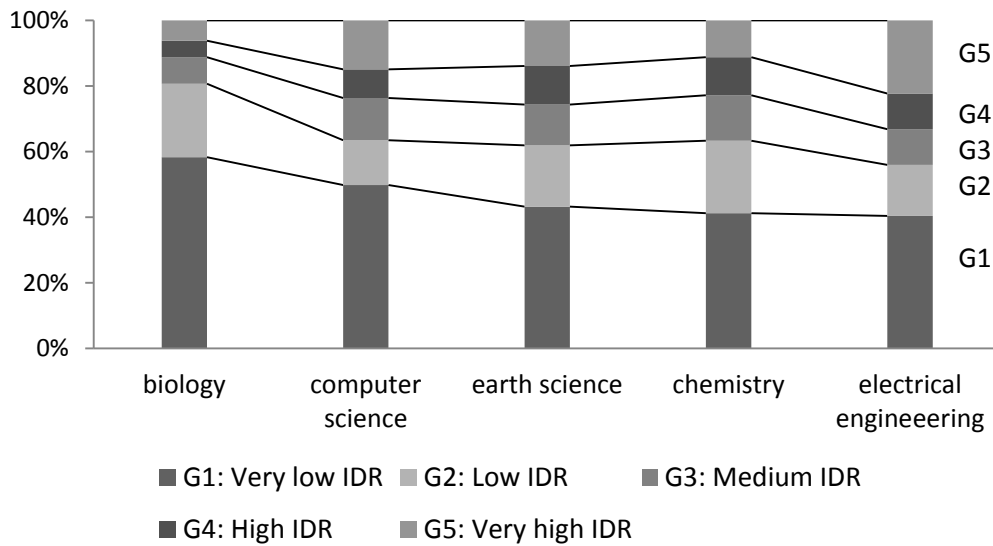


Figure 20 Distribution of Five Groups Classified Based on Calculated Percentage of IDR Papers in Each Discipline

Figure 19 and 20 demonstrate the distribution of the five groups in each discipline. We can see that physics is the least interdisciplinary: over half of physicists in the sample are in the very low IDR group, and only 20 percent in the high or very high IDR group. The two graphs both show that the total shares of group 2 and 3 are almost same for these disciplines except physics. The main differences among these disciplines lie in the shares of group 1, 4 and 5. The disciplines with the high degree of IDR including electrical engineering, chemistry and earth science have fewer scientists in group 1 (very low IDR group) and more scientists in group 4 and 5 (high or very high IDR group) than the disciplines with the low degree of IDR like computer science and biology.

Moreover, the study compares the average percentage of IDR papers between scientist groups, as shown in Table 14. There are several findings worthy of discussion. The first row shows the comparison results for the whole sample. We can learn that female scientists report significantly higher percentage of IDR papers than male, and the calculation using publication data also shows that female scientists have significantly higher percentage of borrowing and boundary crossing papers than male. Contrary to my expectation, however, the self-reported and calculated percentages of IDR papers are both significantly higher for untenured faculty than tenured faculty. Academic scientists with industry experience as a whole show higher degree of IDR than those without industry experience, but the difference is only significant in the calculated percentage of IDR papers.

Table 14 Comparison of Percentages of IDR Papers between Different Groups

Discipline		Gender			Tenure Status			Past Industry Experience		
		Male	Female	Dif	Tenured	Untenured	Dif	With Ind	Without Ind	Dif
FULL	R	.35	.39	**	.35	.40	***	.41	.36	
	C	.31	.34	*	.31	.36	**	.37	.32	*
EAS	R	.41	.50	**	.41	.56	****	.57	.45	
	C	.33	.35		.31	.40	**	.26	.34	
EE	R	.41	.40		.38	.46		.43	.40	
	C	.39	.43		.39	.45		.44	.40	
CS	R	.26	.34	**	.29	.30		.32	.29	
	C	.28	.38	**	.32	.32		.34	.32	
CHEM	R	.41	.48		.41	.52	**	.50	.44	
	C	.31	.36		.32	.38		.45	.33	
BIOL	R	.34	.28		.30	.34		.29	.32	
	C	.24	.20		.22	.24		.27	.22	
PHYS	R	.27	.29		.30	.23	*	.57	.21	***

Note: R: Self-Reported Percentage of IDR Papers, C: Calculated Percentage of IDR Papers
 * p<0.10; ** p<0.05; *** p<0.01; **** p<0.001; the sample size drops for the full model.

Table 14 also shows the differences between distinct scientists groups in terms of their average percentage of IDR papers in each discipline. Biology and physics are two disciplines which have very different comparison results from other disciplines. Biology is the only discipline in which male scientists have higher percentage of IDR papers than female in both self-reported and calculated indicators. Physics is the only discipline in which tenured faculty reports significantly higher percentage of IDR papers than untenured faculty. In most disciplines, female scientists and untenured scientists show higher degree of IDR than male and tenured, respectively, in terms of the percentage of IDR papers. Specifically, ANOVA analyses indicate that the gender difference in the

degree of IDR is significant at the .05 level in earth science and computer science; untenured earth scientists and chemists also have significantly higher percentage of IDR papers than their tenured counterparts. Another interesting finding is that only in physics, scientists who have worked full time for private industry report significantly higher percentage of IDR papers than scientists without industry experience.

4.1.4 Characteristics of Scientists' IDR in Each Discipline

In this section, I will summarize the above descriptive analyses to characterize interdisciplinary activities of academic scientists in each discipline.

Earth Science. Earth science is known as a young and interdisciplinary discipline. Earth scientists' IDR is characterized by working more within their own circle: publishing more IDR papers within their own disciplines rather than publishing outside earth science. Earth scientists in the survey sample have the highest average IDR score, showing that they borrow knowledge and information from a number of distinct disciplines and publish interdisciplinary papers in their own earth science fields. But they are low in boundary crossing: their average percentage of papers published in other disciplines is the lowest, which is only 14%. Another important characteristic is that untenured earth scientists consistently show higher degree of IDR than tenured in all indicators: untenured have higher IDR score, publish higher percentage of papers outside earth science, and report higher percentage of interdisciplinary papers than tenured.

Physics. Physics may be the oldest and most traditional disciplines among the six scientific disciplines our survey covers. Because only one indicator based on survey data is applied in physics, the information about physicists' IDR is very limited. But I still believe that physics is the least interdisciplinary field. Compared with scientists in other

five disciplines, academic physicists in the sample report the lowest percentage of interdisciplinary papers. Contrary to earth science, untenured physicists show lower degree of IDR in their productions than tenured. In addition, physicists who have work experience in industry report higher percentage of IDR papers than physicists without industry experience.

Electrical Engineering. Electrical engineering is very highly interdisciplinary. Unlike earth scientists who are only strong in borrowing, scientists in electrical engineering not only have very high IDR score, but also publish the average highest percentage of papers in other disciplines. Hence, electrical engineers' average calculated percentage of IDR papers is also the highest among the six disciplines. In electrical engineering, there are no statistical differences in terms of IDR degree between different groups (e.g. male group and female group, tenured group and untenured group).

Computer Science. Computer science and electrical engineering are two most application-oriented disciplines in our survey. Both of them have the most scientists with industry experience. But they are very different regarding the degree to which they engage in publishing interdisciplinary papers. Contrary to highly interdisciplinary electrical engineering, computer science is a discipline with low degree of interdisciplinarity. Computer scientists have the lowest average IDR score and the lowest percentage of papers published in other disciplines. Another important characteristic of computer science is that female scientists consistently show higher interdisciplinarity than male: female computer scientists in the sample have higher IDR scores in their publications, publish higher percentage of papers outside computer science, and report higher percentage of interdisciplinary papers than their male counterparts.

Chemistry. Overall, chemistry is a relatively highly interdisciplinary field. Chemists in the survey show high degree in borrowing and boundary crossing. Chemists' average percentage of papers published outside chemistry is 22%, only second to electrical engineering, and their average IDR score is 0.39, only second to earth science. Chemists who have had worked in industry show higher degree of borrowing and boundary crossing than those without industry experience. Chemists also estimate about 45% of interdisciplinary papers in their recent publications, and untenured report more than tenured.

Biology. Overall, the interdisciplinarity of biology is low. Biologists' average IDR score is 0.37, and average percentage of papers in other disciplines is 15%, both of which rank the second last, only slightly higher than computer science. Different from other disciplines in the survey, biology is the one discipline in which male scientists show higher IDR degree in their production outcomes than female: male biologists have higher average values in both self-reported and calculated percentages of IDR papers than female biologists, and male are stronger in both borrowing and boundary crossing than female, but these differences are not statistically different.

4.2 Regression Analysis

So far this chapter has made many descriptive analyses of independent variables and dependent variables. This section will focus on presenting results of running regression analysis with these variables.

4.2.1 Regression Results for the Full Sample

First of all, I regressed the self-reported percentage of IDR papers for the full sample including all six disciplines¹². Except for the four independent variables, I also add the disciplines as control variables in the regression model. The model I used is a GLM with a logit link and binomial family, given that the dependent variable is a fractional variable bounded between 0 and 1. The first column of Table 15 reports the logit coefficients. Because the sample size is not large, I choose to highlight all coefficients at the .10 or better significance level. It can be seen that male has a significant and negative coefficient, showing that female scientists are predicted to report higher percentage of IDR papers than male scientists, which is in line with my hypothesis. However, contrary to my hypothesis, untenured faculty is predicted to have higher self-reported percentage of IDR papers than their tenured counterparts, indicating that untenured faculty tends to engage in research with a higher degree of interdisciplinarity. The coefficients on industry experience and university climate for IDR are not significant. But we can see that industry experience has a positive coefficient with large z-statistics (in parentheses).

¹² I did not regress the calculated percentage of IDR papers for the full sample with all six disciplines because physics is not available.

Table 15 GLMs for the Percentages of IDR Papers for the Full Sample

Dependent Variable	Full Sample with 6 Disciplines	Full Sample with 5 Disciplines (CHEM, CS, EE, EAS, BIOL)		Full Sample with 4 Disciplines (CHEM, CS, EE, EAS)	
	Self-Reported	Self-Reported	Calculated	Self-Reported	Calculated
Tenured	-.197** (-2.37)	-.322**** (-3.58)	-.190** (-2.01)	-.355**** (-3.56)	-.209** (-2.01)
Univ. Climate for IDR	-.003 (-.34)	-.002 (-.20)	.013 (1.49)	-.003 (-.38)	.017* (1.67)
Male	-.128* (-1.67)	-.133 (-1.63)	-.129 (-1.50)	-.248*** (-2.73)	-.209** (-2.18)
Industry Experience	.223 (1.62)	.086 (.61)	.087 (.56)	.097 (.67)	.077 (.47)
Chemistry	-.040 (-.34)	-.039 (-.33)	-.033 (-.27)	-.039 (-.33)	-.034 (-.27)
Biology	-.589**** (-4.74)	-.588**** (-4.73)	-.558**** (-4.17)		
Electrical Engineering	-.225* (-1.74)	-.204 (-1.58)	.287** (2.02)	-.203 (-1.56)	.296** (2.07)
Computer Science	-.715**** (-5.61)	-.693**** (-5.44)	-.086 (-.63)	-.693**** (-5.43)	-.081 (-.59)
Physics	-.770**** (-5.81)				
Observations	1556	1293	1229	1026	972

Notes: Robust z-statistics in parentheses. Earth Science is the reference group. Coefficients significant at * 10%, ** 5%, *** 1%, **** 0.1%.

Next, I performed two GLM analyses on both self-reported percentage of IDR papers and calculated percentage of IDR papers in the full sample including five

disciplines (physics is excluded), respectively. Comparing the two regression results in the second and third column of Table 15, we can find that the relationships between the four independent variables and dependent variables are consistent in the two models. Untenured scientists' self-reported percentage and calculated percentage of IDR papers are both significantly higher than tenured, holding the other variables at the same values for tenured and untenured. The coefficients on the three independent variables: university climate for IDR, male and full-time industry experience are all insignificant in the two models. But we can see that male is consistently negative with large z-statistics.

Because the reference group is earth science in the two models for the sample with 5 disciplines, the coefficient on each discipline represents the difference of the average percentage of IDR papers between the discipline and earth science. We can see that in both of the two models, biologists as a whole show significantly lower degree of interdisciplinarity than earth scientists, and the average percentage of IDR papers for chemists is also lower than earth scientists but the difference is not significant.

The main differences between the two regression model results lie in the coefficients on electrical engineering and computer science. In the model for self-reported percentage of IDR papers, electrical engineering and computer science both have negative coefficients, indicating that earth scientists report higher percentage of IDR papers than the two disciplines but the difference is significant only in computer science. In the other model, the average calculated percentage of IDR papers for earth scientists is significantly lower than electrical engineering and not significantly different from computer science. The changes show that if we believe that earth science has the highest degree of IDR, the calculated percentage of IDR papers as a measure of the overall

degrees of IDR may either underestimate the IDR degree of earth scientists or overestimate the IDR degree of scientists in the two applied disciplines - computer scientists and electrical engineers.

As mentioned earlier, the coefficients on male are negative with large z-statistics in the two models. One possibility is that the gender effect is mediated by biology, because the descriptive analysis has shown that biology is the only discipline in which male scientists have a higher percentage of IDR papers than female. Hence, I ran two more regression models for the sample without biology, shown in the last two columns of Table 15. After I drop biology from the sample, male is negative and significant in the two new models, which is in line with my hypothesis that female scientists engage in a higher degree of IDR than male scientists. The other new finding is the coefficient on university climate for IDR turns out to be positive and significant at the 10% level, indicating that university climate for IDR may have a positive impact on the overall degree of IDR for the sample of scientists in the four disciplines. In addition, industry experience is still not significant in the two new models, showing that there is no statistically significant difference in the overall degree of IDR between scientists with industry experience as a whole and scientists without experience in industry.

4.2.2 Regression Results for Each Discipline

Furthermore, I performed the regression analyses in each discipline. The regression results are presented in two tables. Table 16 includes three less interdisciplinary disciplines: physics, biology and computer science, and Table 17 has three more interdisciplinary disciplines: electrical engineering, earth science and chemistry.

Table 16 GLMs for the Percentage of IDR Papers in PHYS, BIOL and CS

	PHYS		BIOL		CS	
	Self-reported		Self-reported	Calculated	Self-reported	Calculated
Tenured	.412* (1.81)		-.209 (-.98)	-.106 (-.45)	-.025 (-.11)	.047 (.21)
Univ. Climate for IDR	-.003 (-.17)		.010 (.55)	-.002 (-.10)	.002 (.09)	.012 (.54)
Male	-.151 (-.70)		.361* (1.87)	.253 (1.31)	-.389* (-1.95)	-.447** (-2.18)
Industry Experience	1.311** (2.49)		-.183 (-.30)	.210 (.44)	.199 (.82)	.152 (.57)
Observations	263		267	257	256	241

Notes: Robust z-statistics in parentheses. Earth Science is the reference group. Coefficients significant at * 10%, ** 5%, *** 1%, **** 0.1%.

Table 17 GLMs for the Percentage of IDR Papers in EE, EAS and CHEM

	EE		EAS		CHEM	
	Reported	Calculated	Reported	Calculated	Reported	Calculated
Tenured	-.323 (-1.54)	-.221 (-.96)	-.550*** (-3.06)	-.385* (-1.92)	-.446** (-2.21)	-.196 (-1.04)
Univ. Climate for IDR	.008 (.32)	-.003 (-.11)	-.010 (-.63)	.006 (.32)	-.007 (-.45)	.042** (2.68)
Male	.102 (.50)	-.100 (-.46)	-.375 (-2.29)	-.047 (-.25)	-.274 (-1.54)	-.229 (-1.33)
Industry Experience	.032 (.12)	.08 (.30)	.525 (1.35)	-.472 (-.91)	.032 (.09)	.461 (1.06)
Obs.	205	192	285	273	280	266

Notes: Robust z-statistics in parentheses. Earth Science is the reference group. Coefficients significant at * 10%, ** 5%, *** 1%, **** 0.1%.

First, by comparing the two tables, we can see that the coefficients on tenure are very distinct. In the table of three less interdisciplinary disciplines, tenure has a positive and significant coefficient in the least interdisciplinary physics, and negative but insignificant coefficients in the other two disciplines. By contrast, in the table of three more interdisciplinary disciplines, the coefficients on tenure are either significantly negative or negative with large z-statistics. This finding shows that the effects of tenure on the overall degree of IDR may be different in distinct disciplinary communities.

Second, university climate for IDR and having work experience in industry appear to have few impacts on the percentage of IDR papers. There are only two exceptions. One is university climate for IDR is positive at the .05 significance level in chemistry in the model for the calculated percentage of IDR papers. The other is physicists with full-time work experience in industry report significantly higher percentage of IDR papers than those without industry experience.

Third, when looking at the coefficients on male in each discipline, we can find that male is consistently negative and insignificant in Table 17. But male has large z-statistics in earth science and chemistry. In the table including three less interdisciplinary disciplines, we can see that consistent with the earlier descriptive analysis, biology is the only discipline in which male is significantly positive, showing that male biologists are predicted to report higher percentage of IDR papers than female biologists. Contrary to biology, the coefficients on male in computer science are significantly negative in both of the two models on the self-reported percentage of IDR papers and calculated percentage of IDR papers.

So far my interpretations of regression results of all models are mainly focused on the direction of relationship between independent and dependent variables. In a logit regression model, the log-odds of dependent variable are linear functions of independent variables. The coefficient on an independent variable represents the change in the log-odds of dependent variable from a one-unit increase in the independent variable, holding constant the other variables in the model. But the impacts of independent variables on the dependent variable are nonlinear functions, which depends on all variables' values simultaneously. In this study, it is impossible to list the predicted percentage of IDR papers for all possible cases. For the models run in each single discipline, I briefly discuss a few typical examples for significant variables. For instance, a female and tenured physicist without industry experience in an institution with 30% STEM doctorate recipients reporting interdisciplinary dissertation fields is predicted to report 30.9% of IDR papers in her work, 8 percentage points higher than an untenured physicist with the same characteristics. The percentage of IDR papers for a male and untenured computer scientist without industry experience in an institution with 40% STEM doctorate recipients reporting interdisciplinary dissertation fields is computed as 25.8%, 8 percentage points lower than a female computer scientist with the same characteristics.

In a brief summary, this chapter characterizes interdisciplinary activities of scientists in distinct disciplines by statistical analysis of their engagement in borrowing and boundary crossing. Using two variables – the self-reported percentage of IDR papers and calculated percentage of IDR papers to measure the overall degree of IDR, I perform regression models in the full sample and each discipline to test the hypotheses developed earlier. Results show that the effects of different factors on the degree of

interdisciplinarity do differ by discipline. Key findings will be highlighted in the next chapter.

CHAPTER 5: CONCLUSIONS

5.1 Overview

Today when IDR is becoming increasingly important in generating innovative research and solving complex problems in academia, discussions of IDR antecedents, processes and outcomes are becoming increasingly important in research policy and sociology of science. Different from most IDR studies focusing on bibliometric research of scientists' outputs and collaborative research of interdisciplinary processes, this study addresses two primary questions: 1) what individual and organizational factors affect academic scientists' engagement in IDR; 2) what are the effects of these factors in different disciplines. Even though there are a few empirical studies on this topic, they have a lot of limitations. The following points distinguish this study from existing studies:

- Based on Pierce's framework, this study sees interdisciplinarity as a multidimensional concept which includes three types of IDR: borrowing, collaboration, and boundary crossing. By focusing on scientists' production outputs, it creates two bibliometric indicators to measure borrowing and boundary crossing, respectively.
- It uses both survey data and bibliometric data to develop two dependent variables: self-reported percentage of IDR papers which is from researchers' own estimate of their IDR papers responding to one survey question, and calculated percentage of IDR papers which is a combination of two facets of scientists' IDR publishing activities - the percentage of borrowing papers and boundary crossing papers.

Both of the two dependent variables measure the overall degree to which scientists engage in publishing interdisciplinary papers but they are generated based on different techniques, which improve, to a great extent, the reliability of measurement.

- It pays particular attention to the distinctions among disciplines. It characterizes interdisciplinary activities of scientists in each discipline based on descriptive analysis of borrowing and boundary crossing indicators. Using both the bivariate and the multivariate analyses, it explores the different effects of the independent variables on different dimensions of interdisciplinarity in different disciplines.
- Regarding the study's research scope, the data involved in this study are broad: 1598 survey respondents in 6 scientific disciplines from 149 Research Extensive Universities, and 13809 papers published by the respondents between 2003 and 2007.

5.2 Key Findings

This study finds many interesting and important research results, presented and reported in Chapter 4. Here I highlight a few key findings.

First, I find that some of our conventional wisdoms about traditional academic departments are outdated. One of my hypotheses was that untenured faculty is less likely to engage in highly interdisciplinary work than tenured, which is built the conventional perception that academic departments' evaluation culture may not value interdisciplinary work. Prior studies believe that untenured scientists are not willing to take risks to conduct IDR before they receive tenure because 1) IDR is more time-consuming, more complicated, and more difficult than disciplinary research, and thus it

may delay tenure (Heberlein 1988, Golde and Gallagher 1999, Pfirman 2005, McCoy and Gardner 2012); 2) scientists would find it more difficult to publish IDR papers in prestigious disciplinary journals and IDR papers may not be valued by disciplinary departments (Bruce, Lyall et al. 2004, Reich and Reich 2006, Pfirman, Martin et al. 2007, Blackwell, Wilson et al. 2009); 3) university evaluation system may not favor research across disciplinary boundaries because academic departments still follow discipline lines (Thi and Lahatte 2003, Payton and Zoback 2007). I also hypothesized that academic scientists who worked full-time in private industry are more likely to engage in interdisciplinary work than those without industry experience. This hypothesis is built on prior studies which assume that industry experience is a big plus for academic scientists to develop their IDR (Carayol and Thi 2005, van Rijnsoever and Hessels 2011), because these outsiders from private industry may be more oriented to application and have more opportunities to be exposed to newly interdisciplinary technologies than insiders following academic career paths.

However, the research results show that these two expectations only apply in physics, not in other disciplines. As a more traditional discipline, the focus in physics still seems to be disciplinary. Among the six scientific disciplines this thesis studies, physics is the least interdisciplinary: physicists report the lowest average percentage of IDR papers. In such a uni-disciplinary environment, the department's evaluation culture is usually discipline-based (Blackmore and Kandiko 2011). Untenured scientists would face more serious challenges when working on IDR, as I discussed above. They appear to be more conservative, and thus are less likely to be involved in interdisciplinary work than tenured scientists. The regressions for the self-reported percentage of IDR papers

across all six disciplines also show that the coefficients on tenure and industry experience are both significantly positive only in physics. Therefore, the research findings in physics align with conventional assumptions: untenured physicists are less interdisciplinary than tenured, and physicists with industry experience are more interdisciplinary.

Contrary to the conventional perception, however, the analysis results show that untenured scientists in highly interdisciplinary fields such as earth science and chemistry are involved in IDR to a higher degree than tenured ones. Even in less interdisciplinary fields such as computer science and biology, findings show that there is no significant difference in interdisciplinarity between tenured and untenured scientists. Is it because institutional environment is becoming more friendly to IDR in these fields so that the challenges for engaging in IDR become easier for junior scientists, or because junior scientists themselves in these fields are more interested in and more enthusiastic about IDR? Many studies on IDR have discussed relevant issues. For example, some researchers argue that younger scientists are more open to new interdisciplinary research (De Boer 2006), and “likely to have had more interdisciplinary exposure and less intellectual commitment to a particular field” (Rhoten 2004, p.2046). Meanwhile, several bibliometric studies show that academic disciplines are becoming more interdisciplinary (Van Rann 2000, Braun and Schubert 2003, Porter and Rafols 2009). In this study, we also can see that the average percentage of interdisciplinary papers reported by scientists in chemistry and earth science has already been over 40%, according to Netwise survey responses. My calculation also indicates that the percentage of borrowing papers and boundary crossing papers for these two disciplines is over 34%. Then, when IDR has

become very popular in these fields, scientists' interdisciplinary work would be more easily understood and recognized by their senior colleagues in tenure committee. They can find more resources (e.g. collaborators, equipments or funding) to shorten research time. In a survey of leaders from 89 American Research Universities, 60 percent of respondents reported \$1 million or more start-up packages offered to interdisciplinary researchers in sciences (Brint 2005). There may be more journals within their own fields available for publishing interdisciplinary papers. In a recent scientific paper published in *Chemical Communications*, chemists (Braga, Grepioni et al. 2010, p.6232) express their appreciation for "the success of interdisciplinary journals published by major chemical societies" so that they see that the paradigm of crystal forms is changing. When these organizational conditions are becoming favorable to IDR, it is not surprising that untenured scientists are more drawn to IDR because they are more likely to be exposed to new interdisciplinary work. However, it does not mean that junior scientists in these disciplines don't have or perceive risks to working on IDR at their academic careers. In the forum of a recent geophysics magazine for the American Geophysical Union, researchers discussed the professional risks and challenges young scientists perceive and the main concern is still on the issue that IDR may be unrewarded in the academic sector (Fischer, Mackey et al. 2012).

Likewise, contrary to the conventional wisdom that people with industry experience are more interdisciplinary, results show few differences in the degree of interdisciplinarity between faculty with and without industry experience. The only exception can be observed in physics. A possible reason is that in a traditional discipline department like physics, the overall academic culture is still discipline-based, and the

average IDR degree of faculty members is low, which would provide fewer opportunities for insiders to get interdisciplinary exposure. In such traditional departments, therefore, outsiders from private industry may be more likely to work on IDR than insiders. In more interdisciplinary disciplines, scientists following the traditional academic career paths have many opportunities and resources to understand and get involved in IDR. In these fields, there may be no significant difference of interdisciplinarity between scientists with industry experience and those without the experience.

The second key finding is that the hypothesis that female scientists are more likely to engage in highly interdisciplinary work than male is not consistently true across all six disciplines. Research findings show that the gender hypothesis works in many cases. Table 15 reports that female scientists in chemistry, computer science, earth science and electrical engineering as a whole group are predicted to engage in IDR to a higher degree than their male counterparts. When looking at each discipline, the coefficient on male is also consistently negative, even though not all of them are significant. However, the gender effects appear to be opposite in biology. We can find that male biologists are predicted to report higher percentage of IDR papers than female biologists. Compared with the other five scientific fields where females are largely under-represented, biology is the one with little gender gap. The recent statistics data from NSF (2010a) show that the proportion of female scientists is 52% in biology, compared to 36% in chemistry, 23% in computer science and earth science, 18% in physics and 13% in engineering. So female biologists are well represented and in equally competitive positions compared with their male counterparts. Then, why are female scientists in biology less interdisciplinary than male but females in other S&E fields more

interdisciplinary than their male counterparts? This question needs to be understood in the context of factors that account for the different proportion of women in biology and other science disciplines. In a recent study of 2,500 biologist and physicists at top U.S. research universities, the scholar (Ecklund 2012) found that scientists themselves identified social-cultural or organizational factors (e.g., gender discrimination), gender differences and individual choices (females are more drawn to biological research which is often connected to concrete concepts and emotional contents than physics connected to abstract mathematics), and stereotypes as main factors accounting for women's higher representation in biology. In this study, I find that female scientists in biology are less engaged in IDR than male but females in other science disciplines conduct more interdisciplinary work than male. We may need to further investigate in the future studies whether it is an effect of social-culture or organizational factors or a result of women's own career choices, or the function of these combined together. For example, a possibility is females who choose biology are the group who don't like to work at the interface between different disciplines, while females in other S&E fields are those who are better in integrating different knowledge. The other possible reason could be considerations of sociocultural or organizational factors, which have been widely discussed in studies of women in science (Zuckerman 1991, Valian 1999, Fox 2001). Rhoten and Pfirman (2007) indicated that in current organizational practice and reward systems, female scientists are less competitive to male so that females in male-dominated fields may prefer to choose a relatively new research area in order to avoid competing with males.

Another finding is that scientists in different disciplines show distinct characteristics with regard to their interdisciplinary work. Based on the descriptive analyses, for example, earth science and electrical engineering are both highly interdisciplinary fields. But they have different preferences for working on IDR: earth scientists are more likely to work within their own circles rather than work across boundaries (more borrowing and less boundary crossing); by contrast, electrical engineers are strong in both borrowing and boundary crossing. These findings imply that distinctions between disciplines should be taken into full account when evaluating scientists' research work.

5.3 Contributions to Theory

The major contribution of the research is it expands the current studies on IDR, especially extending understanding of individual scientists' interdisciplinarity in different disciplines. The conceptual model of IDR sees interdisciplinarity as a multi-dimensional concept, identifies three types in the transfer of information: borrowing, collaboration, and boundary crossing, and analyzes the relationship among them. This study applies the conceptual model to empirical studies of IDR, and finds that the effects of individual and institutional factors on the overall degree of IDR of individual scientists in distinct disciplines are different. It suggests that researchers studying scientists' interdisciplinary behavior do need to take a multi-dimensional conceptual view of interdisciplinarity, and consider the distinctions between different disciplines.

The other contribution lies in its research on women in science. Prior studies have discussed, from multiple theoretical perspectives, that women possibly have greater preference for interdisciplinarity (Rhoten and Pfirman 2007, van Rijnsoever and Hessels

2011). However, those studies not only lack solid evidence to support the statement, but do not consider the contextual differences between disciplines. The research of this dissertation makes a comprehensive comparison between males and females among different disciplines regarding their interdisciplinarity. Research results find that whether females are more drawn to IDR in one discipline depends on the prevalence of women in the discipline, and suggest us to investigate the reasons for it from the multiple perspectives.

5.4 Implications for Policy

We have seen that science policy makers, funding agencies and university administration have made great efforts and are still working hard to promote IDR. Then, what are the implications this study can provide for them when they make decisions? First, they need to keep fresh and informed about scientists' research activities and underlying contexts. This study finds that the conventional perceptions about who are more likely to engage in IDR have outdated, because they are built on traditional views of academic departments. Nowadays many scientific fields have become highly interdisciplinary. The academic department environments in these fields are probably open to or supportive of IDR. Untenured scientists publish higher percentage of interdisciplinary papers than we assumed. When facing the situation, how should a discipline department adjust its evaluation system to give appropriate assessment to its faculty members' interdisciplinary work?

It is important for university administrators to take into full account distinct characteristics of different disciplines when they make or reform policies to encourage faculty members to work on IDR. "Although it is evident that disciplines have their

distinctive cultural characteristics, this consideration tends to be largely overlooked in research into, as well as policy-making within, higher education” (Becher 1994, p.151). The research shows many differences in IDR among the six scientific fields. When university administrators consider possible instruments to boost IDR around the campus, they may need to understand these differences and take advantage of the characteristics of each discipline.

Science policy makers and funding agencies may need to consider how to develop appropriate indicators to measure IDR for their statistical analysis. This study has shown that interdisciplinarity is a multi-dimensional concept. Capturing only one aspect is not enough to give a comprehensive estimate for the overall degree of IDR. For instance, the variable “the proportion of STEM students reporting interdisciplinary dissertation research fields” this study uses to measure university climate for IDR is from the SED. It may be necessary to reconsider why we need this indicator, and what this indicator actually measures, and whether we can design better survey question to serve our goals.

5.5 Limitations

This study also has a few limitations worthy of mentioning. Here, I will discuss three main limitations in hypothesis development, model building, and indicator measurement, respectively.

First, other individual and organizational factors may have effects on IDR. For example, the departmental contexts may play an important role in affecting individual scientists’ engagement in interdisciplinarity, e.g. departmental support for IDR. At the individual level, scientists’ educational and training experience in different fields is also a key factor affecting their likelihood of pursuing an interdisciplinary initiative in their

academic careers. These factors could be taken into account in hypotheses development. However, because of the lack of data or measurement issues, I did not include them in my models, which is a big limitation of this study.

Second, there exists an endogeneity issue in developing models predicting the degree of IDR. For example, my model states that academic scientists in universities with better climate for IDR are more likely to engage in interdisciplinary work. However, probably it is the case that scientists who enjoy interdisciplinary work choose to develop their professional careers in universities with more supportive attitude towards IDR. A solution to the endogeneity problem is to add instrumental variables to the model. But I have not found good instruments from the current data to address this issue, which is another limitation of the study.

Third, this study develops two bibliometric indicators to measure borrowing and boundary crossing. Each has shortcomings (partly discussed in Table 9). The percentage of papers published in other disciplines is subject to the rough classification of seven broad science fields, which might not be very accurate. The calculation of IDR score relies largely on the correlation matrix of SCs, which needs to be updated timely. In addition, this study uses two dependent variables to measure the overall degree of IDR. Their correlation value is not very high, and each of them has limitations, as I have discussed in Chapter 3. These measurement issues should be identified and taken into account.

5.6 Future Research Directions

This study has made comprehensive quantitative analyses of what individual and organizational factors affect academic scientists' engagement in highly interdisciplinary

work and their effects in different disciplines, and generated many interesting findings. For example, not in line with the hypotheses I developed initially, untenured scientists show greater interdisciplinarity in three highly interdisciplinary disciplines. The gender hypothesis is also not consistently true across all six disciplines. The study has discussed some possible reasons for these findings. But, in order to better understand them, it is necessary to develop deeper qualitative analysis such as interviews or focus group to explore the critical factors explaining the research results in the context. It might be a possible research direction for future research.

The other possible research direction is to investigate how to develop a good indicator to measure IDR. In this study, by focusing on scientists' production, I use the percentage of IDR papers to measure the overall degree of IDR. But this indicator only captures scientists' publishing activities. It does not cover scientists' other IDR activities such as grant proposal and patent application. Further exploring the measurement issue may have potential importance in contributing to IDR studies.

APPENDIX

Comparison of Different Bibliometric Measures of Interdisciplinarity

Measures	Methods	Pros	Cons	Studies
Co-author	Analyze co-occurrences of different disciplinary departmental affiliations of co-authors on the same paper.	a) It captures social practices of a discipline by seeing authors' departmental affiliations; b) it does not rely on classification of knowledge which is often inadequate and distorted.	a) Authors' departmental affiliation may not represent accurately the disciplines in which they are actually doing research. b) it is difficult to assign a discipline to authors from industry or government.	(Qin, Lancaster et al. 1997, Steele and Stier 2000, Schummer 2004)
Co-word	Analyze co-occurrences of discipline-specific keywords in papers	It has a good focus on the knowledge information of a paper, and can be applied to some situations where there are fewer citing practices.	Because the classification schemes (key words) are a bit narrow, the approach is only applicable in homogeneous fields of study.	(Rip and Courtaal 1984, Morillo, Bordons et al. 2001)
Citation Analysis	Analyze citations between papers in different disciplines	It can measure knowledge flow between disciplines by looking at papers' citations across disciplines	Limited in the applied sciences and technology which have fewer citations.	(Porter and Chubin 1985, Tomov and Mutafov 1996)
Co-classification	Analyze co-occurrences of different discipline-specific headings.	It would be better applied in larger fields than co-word analysis, because its classification schemes often have a broader basis.	a) It cannot be well applied to the recent research because of the rigidity of classification systems; b) the classification relies largely on expert assessments of assignment of headings.	(Tijssen 1992)
References	Analyze disciplinary categories of references one	It can assess the diversity of disciplines which are used in the	a) It has a limitation in the areas which often have fewer references. b) The disciplinary	(Sanz-Menendez, Bordons et al. 2001, Rafols

Measures	Methods	Pros	Cons	Studies
	paper cites based on the journals in which references are published.	research process by looking at the authors' readings.	categories of references are not necessarily the same as the journals in which they are published.	and Meyer (2007)

Table References: Some ideas adapted from Rip and Courtial (2004) , Schummer (2004), and Rafols and Meyer (2007).

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