THREE ESSAYS ON INTERDISCIPLINARITY AND KNOWLEDGE PRODUCTION

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ABSTRACT

Ashton M. Verdery: Three Essays on Interdisciplinarity and Knowledge Production
(Under the direction of Barbara Entwisle)

There is a broad contemporary interest in innovation, how ideas interconnect (or fail to), and how they relate to organizational structures and research funding. Those interested in enhancing innovation have initiated policies, formal and informal, to quicken its pace, ranging from dramatic increases in federal funding to calls and moves to reshape longstanding organizational features of research universities and professional associations. In this dissertation, I examine some of these policies and their outcomes using tools from text analysis and network science. I first look at whether the doubling of the National Institute of Health's budget between 1998 and 2003 enabled a scientific revolution. I then explore the prevalence of interdisciplinarity in dissertation committees and whether dissertations with interdisciplinary committee members tend to examine more novel topics. After this, I explore the prevalence and nature of interdisciplinary research collaborations among contemporary core demographers. I conclude by reflecting on how these chapters shed light on the production, organization, and advancement of knowledge.

To Amanda Byrd

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CHAPTER 1. OVERVIEW

Can large increases in federal funding buy a scientific revolution? How does the structure of dissertation committees relate to the novelty of research pursued in dissertations? How segregated is the co-authorship network of a field with interdisciplinary aspirations? This dissertation asks three questions about interdisciplinarity and knowledge production. There is a broad contemporary interest in innovation, how ideas interconnect (or fail to), and how they relate to organizational structures and research funding. Those interested in enhancing innovation have initiated policies, formal and informal, to quicken its pace, ranging from dramatic increases in federal funding to calls and moves to reshape longstanding organizational features of research universities and professional associations. In this dissertation, I examine some of these policies and their outcomes.

I look at idea generation and innovation from multiple angles and at several organizational scales. The second chapter examines a specific event – a massive expansion of the budget of the National Institutes of Health between 1998 and 2003 – to see whether this dramatic increase in funding changed the structure and organization of scientific research in the biomedical sciences. The third chapter looks at some of the newest ideas being produced in research universities, those put forth in emerging scholars' dissertations. Here, I focus on the associations between the disciplinary composition of dissertation committee members and the ideas researched in the dissertation. I document substantial levels of interdisciplinarity in dissertation committee composition and relate this to the idea structure that is being pursued in contemporary dissertations. The fourth chapter deals with questions about new ideas in a different way. In it, I look at a longstanding field with aspirations to interdisciplinarity, American demography, which is an interesting case because most demographers are not employed in explicit demography departments. I examine whether American demography is better characterized as interdisciplinary, with true synthesis among its members and their research agendas, or multidisciplinary, where members from multiple disciplines communicate but do not synthesize their work.

I use the perspectives and tools of social network analysis to guide my inquiry. Indeed, a variant of one measure of novel combinations, operationalized as observed-expected ratios, appears in each chapter. In the second chapter, I look at novel combinations of keywords on NIH funded applications. In the third, I look at the novel combination of ideas used in dissertations and relate this to the structure of dissertation committees. In the fourth chapter, I look at novel and expected co-authorships among demographers drawn from a range of disciplinary backgrounds. I use vastly different sources of data in each chapter, however. The second chapter draws on the population of funded NIH grants from 1985 to 2013. The third chapter looks at dissertations and their committees in 38 of the largest research universities from 2007 to 2013. The fourth focuses on co-authored papers presented at the annual meetings of the Population Association of America from 2002 to 2014. These rich data sources provide opportunities for me to examine questions about the organization of research, the exploration of new ideas, and the potential for scientific advance that cannot be answered with traditional surveys, comparative historical work, or formal modeling. With them, I am able to interrogate, for instance, the structure of scientific revolutions without relying on case studies of specific historical scientific achievements (Chapter 2). I can also look at the relationship between the examination of new ideas and structural interdisciplinarity in dissertation committee organization at the beginning of academic careers (Chapter 3). Or, I can provide a case study of the level of interdisciplinarity within a widely recognized field that is often touted as being interdisciplinary (Chapter 4). Because these data are not designed for research, using them in this context is also an accomplishment. I used an array of non-standard tools like web scraping, text parsing, and newer approaches to network analysis to achieve this.

Methodologically, my approach is primarily descriptive. The questions I interrogate are new, and the data I use are rich and informative. In this context, descriptive results are interesting in themselves. Answering them will lay the ground work for future studies. A related note is that I eschew many of the standard tools of statistical inference in this dissertation. For one thing, each chapter deals primarily with “populations” of one sort or another: funded NIH proposals in Chapter 2, all dissertations at a set of top research universities in Chapter 3 (though this chapter contains perhaps the closest data structure to a traditional sample), and all core members of American demography, as I have defined it, in Chapter 4. More important, however, is the scale of these data. Many of my analyses focus on pairs or potential pairs – of keywords, dissertation committee members, or demographers – almost always billions of them, frequently reproduced across multiple years (30 in Chapter 2; 7 in Chapter 3; 13 in Chapter 4). For both of these reasons, statistical significance is less important than effect sizes because sampling variance will not play a meaningful role. I have focused many of my methodological designs accordingly around effects and their interpretation.

This dissertation speaks to issues of substantial relevance to current policy debates, both within and outside of universities. The second chapter deals broadly with how the NIH achieves its mission and the potential scientific returns to public investment in federally funded research, but it accomplishes this by focusing on a specific event, the NIH doubling from 1998 to 2003. There are clear policy implications to knowing whether a historically massive funding increase revolutionized the scientific ideas that were pursued in conjunction. If there is no relationship, for instance, then attempts to fund transformative science will need to be targeted carefully. The third chapter has policy relevance because of the large push within universities toward interdisciplinarity in all facets, from undergraduate education to the hiring of faculty. This push is echoed throughout agendas set by research funding agencies. Understanding the role of interdisciplinarity at the nexus of research and education embodied in a dissertation will shed important light on this program, as will understanding variation across areas of study. The fourth chapter speaks also to modern universities and policy makers, because research centers – like those where demographers are frequently associated – are growing in importance and number (Jacobs 2014), and because it addresses a longstanding interdisciplinary field that has strong historical (and perhaps contemporary) connections between academic institutions and extramural research programs not linked to universities. The fostering and maintenance of such connections is an important area of growth for universities and the economy (Geiger and Sa 2009). Demography is also is a field that garners an outsized amount of federal funding, at least within the social sciences, which means that an accounting of its organizational structure is important.

My interest in this dissertation comes from my training. All of my degrees will be in the same discipline, sociology. At the same time, I have spent many years working in interdisciplinary teams. Jane Menken called demography “a coauthoring field”, and I have taken that quite literally, having not yet published a sole authored article. I have also benefitted substantially from the organizational setting in which I have been embedded. Ron Rindfuss (quoted in the *PAA Oral History Project* 1993:403), speaking twenty years ago about the

Carolina Population Center said, “the characterization of the North Carolina program as being multidisciplinary is still true today. It's the only program I can think of that involves faculty members from as diverse a collection of departments as we have.” Twenty years later, I feel that is still the case, and I have benefitted substantially from it. It fascinates me how interdisciplinary research can work, and the synthesis of ideas it can generate. To understand how science evolves and changes, we need to use new data and new approaches. This dissertation makes several first steps in that direction.

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CHAPTER 2: A GIFT TO THE MILLENIUM? THE NIH DOUBLING AND SCIENTIFIC ADVANCE

Introduction

Federal funding of scientific research was at low levels until the launch of Sputnik in 1957; from that point until the current era, funding increased gradually, in both nominal and constant dollars. Aside from brief spikes, the National Institutes of Health (NIH) budget grew an average of 2.6% per year in inflation adjusted dollars from 1980 to 1997. Beginning in 1998, however, four successive Congresses approved five annual increases of more than 10% year-on-year growth that resulted in a doubling of the NIH budget by 2003. This period of sustained growth, the "doubling", was historically unprecedented for the NIH. The goals of the doubling were ambitious: announcing it during his 1998 State of the Union address, President Clinton called the doubling "a gift to the millennium… for path-breaking scientific inquiry… so ours will be the generation that finally wins the war against cancer, and begins a revolution in our fight against all deadly diseases" (Clinton 1998). There was considerable optimism that the doubling in research funding could buy a scientific revolution, a sentiment which has recently been revived in editorials (Gingrich 2015) and congressional initiatives (Upton and DeGette 2015). In light of these goals, it is important to assess whether and how such a dramatic increase in federal research support might have led to a scientific revolution in the United States.

Classic work on the relationship between federal research funding and the production of knowledge provides a strong rationale for governmental investments in basic research (Arrow 1962; Nelson 1959) but offers little guidance for understanding how such a surge in funding may affect scientific revolutions. More recent work has sought to evaluate how federal funding affects research trends using cross-sectional designs that examine whether better funded researchers and universities have more research outputs in the form of publications, patents and citations and has generally found modest effects (Adams and Griliches 1998; Jacob and Lefgren 2011; Payne and Siow 2003; Rosenbloom et al. 2014; Whalley and Hicks 2014). Unknown is whether this work generalizes to the qualitative change in funding regimes that the NIH doubling period represented. In addition, this body of work focuses on the volume of research being conducted rather than its content. Counts of publications, and to a lesser extent citations, are important but not designed to capture the types of revolutionary changes the doubling sought to generate.

Direct attempts at measuring major scientific breakthroughs suffer from a different set of limitations. Commendable work by a number of groups such as the STAR METRICS program, the UMETRICS program, the University of Michigan's IRIS program, and the Alfred P. Sloan Foundation has sought to tie federal research funding to outcomes that include but also go beyond publication and citation counts. One of the key goals is to measure the effects of federal research funding on job creation and economic growth. As an exemplar of this approach, (Lane and Bertuzzi 2011) offer a case-study of how the discovery of tumor necrosis factor enabled the development of many current blockbuster pharmaceuticals, which have had billions of dollars of sales, by historically mapping the citation patterns of these drugs in patent filings. This approach, however, a) focuses on the translation of knowledge into successful applications rather than knowledge production in itself, b) samples on the dependent variable (successful breakthroughs), and c) is difficult to generalize beyond individual cases. Another approach to measuring research translation has addressed long-term impacts of NIH funding by using a demographic approach to relate cohort level mortality rates to lagged NIH research funding in the aggregate and for specific categories of disease (Manton et al. 2009). This approach provides suggestive evidence that historical funding levels correlate with future mortality reductions, albeit in non-linear ways, but it speaks to knowledge translation rather than knowledge production. In this paper, I argue that to measure whether and how the doubling period led to a scientific revolution, we need to examine its effects on the accumulated body of scientific knowledge itself.

The sociology of science literature provides a framework for understanding how the NIH doubling period may or may not have achieved its goals of creating revolutionary scientific breakthroughs. Within a contentious literature, researchers in this tradition generally distinguish between periods of knowledge accumulation and periods of scientific flux (Abbott 2001; Kuhn 1962; Lakatos 1970; Shwed and Bearman 2010). The former is characterized by incremental fact accumulation under a united paradigm in what Kuhn called "normal science". Periods of scientific flux – what Kuhn called "revolutionary science" – by contrast, are characterized by incongruent anomalies between hypotheses and data, which, if persistent, lead to the development of new fields through the splitting of old ones and the emergence of new ways of thinking. The distinguishing feature of revolutionary science is the extent to which ideas are combined in novel ways. In periods of knowledge accumulation, the focus is on ideas that have been examined in combination frequently. During periods of flux, the focus is on combining ideas in new ways. The question is, "can focused investment unleash sudden breakthroughs?" (Evans and Foster 2011:724). Did the doubling of the NIH budget enable a shift from knowledge accumulation to revolutionary flux? If it did, what form did it take?

There are reasons to suspect that the NIH doubling period had the potential to enable a scientific revolution. Research on scientists' research strategies suggests that scientists face an "essential tension" that forces them to choose between focusing on either traditional, low risk-low reward, incremental research that facilitates productivity and stable career advancement or on innovative, high risk-high reward research that may lead to the appearance of non-productivity, but which, if successful, can yield large returns to the researcher and broad scientific influence (Foster, Rzhetsky, and Evans 2013). Faced with the choice between tradition and innovation, most scientists choose tradition, because innovation so rarely pays off, but those that do focus on innovative strategies that combine unexpected ideas are more likely to win prestigious awards and be highly cited, assuming they are able to publish their papers at all (Foster, Rzhetsky, and Evans 2013; Uzzi et al. 2013; Leahey and Moody 2014).

When new ideas are combined in novel ways more frequently, we can expect that science will advance more quickly and, perhaps, even revolutionize. Weitzman (1996, 1998) argues that the combination of novel ideas is the primary source of new knowledge creation through so-called "recombinant innovation". Olsson (2000) situates this argument in a dynamic topological space, arguing that topologically closer ideas are similar on relevant dimensions and that paradigm shifts occur when ideas that are further apart are successfully combined (see also Poincare 1908 [1952]). To foster innovation, Foster, Rzhetsky, and Evans (2013:8) provide two policy interventions that would promote risk taking: 1) decoupling scientists' early career job security from productivity, and 2) lowering barriers to risky projects with determined funding. The NIH doubling, by increasing the amount of funding available in the biomedical sphere, may have had both effects, at least temporarily, thereby encouraging the types of risky projects that would lead to large impacts.

Did the NIH doubling period fund a scientific revolution? To answer this question, I search for novelty by examining the dynamic network of keyword combinations used in over three hundred thousand competing NIH grant applications that were successfully funded for the first time during the period 1985-2008. I give special attention to differences between applications funded before, during, and after the doubling period (1998-2003). Prior work on the topic of federal research funding's effects suggests that the increased amount of money awarded may have led to marginally more publications, but this does not address the novelty of research conducted or any notion of paradigmatic shifts in science. I use insights from the sociology of science, measures from network science, and an interrupted time series approach to test whether the NIH doubling period achieved its stated goals. Because the doubling period was a political decision made by four separate Congresses, partially exogenous to events occurring in science which did not directly affect trends in the availability of research outlets in terms of peer-reviewed journals, this approach gives substantial leverage toward understanding how science policy and research funding affect what is being researched and sheds light on the production, organization, advance, and rearrangement of knowledge.

The NIH Doubling in Context

Research and development (R&D) is defined as "creative work undertaken systematically to increase knowledge, including knowledge of humanity, culture and society and the use of knowledge for new applications. R&D covers basic research, applied research, and experimental development" (World Bank 2013). The World Bank notes that R&D in all sectors constituted 2.9% of U.S. GDP in 2012. The National Science Foundation estimates that $66 billion were spent on research and development in higher education institutions in the U.S. in FY 2012, the most recent year for which data is available. Of this amount, $40 billion (61%) came from the Federal government with $22 billion coming from the Department of Health and Human

Services, which houses the NIH (National Science Foundation, National Center for Science and Engineering Statistics 2013).

The advance of scientific knowledge does not occur in a policy vacuum. Levels of federal research funding in the contemporary United States can be expected to exert key pressures on the direction of research and the pace of discovery. The NIH's mission is "[t]o seek fundamental knowledge about the nature and behavior of living systems and the application of that knowledge to enhance health, lengthen life, and reduce illness and disability", with the following specific goals mentioned, among others, "foster fundamental creative discoveries, innovative research strategies, and their applications", "develop, maintain and renew scientific human and physical resources", "expand the knowledge base", and "promote the highest level of scientific integrity, public accountability, and social responsibility in the conduct of science" (www.nih.gov/about/mission). Similar goals are reflected in the mission statements of other funding agencies: "[c]reating breakthrough technologies" (DARPA: http://www.darpa.mil/about.aspx), "promote the progress of science" (NSF: https://www.nsf.gov/nsf/nsfpubs/straplan/mission.htm), "promote scientific and technological innovation" (DOE: http://humansubjects.energy.gov/research/doe-mission.htm), and "[t]o reach for new heights and reveal the unknown" (NASA: http://www.nasa.gov/about/#.VK2teHvm7aQ). Understanding the impacts of funding trends at the NIH, the largest federal funder, may help to shed light on the broader goals of federal funding agencies because of such commonalities in their goals.

The NIH discusses how it evaluates its impact on society in its public facing "Impact" web-page, which lists four domains of impact in the following order: health, economy, communities, and knowledge (http://www.nih.gov/about/impact/). It is difficult to quantify the impact of federal funding on health, economy and communities (Lane 2009), though efforts are underway (Lane et al. 2014; Lane and Bertuzzi 2011; Manton et al. 2009). However, metrics for quantifying its impacts on knowledge discovery are underdeveloped. One approach taken by NIH is to cite the number of Nobel Laureates they have funded – 211 or 18% of the 826 ever awarded (http://www.nih.gov/about/impact/knowledge.htm) – but given that they have funded more than 250,000 unique Principal Investigators since 1985, this number lacks context. A similar approach discussed on the NIH impact page is to highlight the important research findings in a given year that were funded by NIH – recently, they highlighted HIV transmission reduction with early treatment, mind control over robotic appendages for paralyzed patients, and key steps toward a universal flu vaccine that would work across flu species (http://www.nih.gov/about/impact/impact_knowledge.pdf). It is difficult to assess the generality of these findings in context because they are selectively chosen from tens of thousands of research projects funded in each year. Because of the volume of findings in any given year, a large-scale and historical view is needed to assess fundamental scientific change; else one could find a few findings in each year that appear to be breakthroughs.

Though the NIH has long been the key source of scientific research funding in the United States, the amount it provides has varied considerably over time as seen in Figure 2.1. The contemporary era is particularly interesting because of its sharp contrasts. In that time-frame, there are three important periods. The first runs from 1985-1997 and is characterized by relatively flat year on year growth, with small fluctuations from year to year. The second period, from 1998-2003, is shaded in the graph and corresponds to the NIH doubling period. Red lines show the linear extrapolation of the prior trend in constant and nominal dollars and highlight how much of a break the doubling period represented from what came before. Indeed, extrapolating the pre-doubling trend shows that current appropriations, in constant dollars, are lower than what would have been the case if the pre-doubling rate of growth was simply sustained unto the present. Since 2004 NIH budgets have been shrinking in constant dollar terms, with the temporary exception of spikes in 2009 and 2010 owing to the supplemental American Recovery and Reinvestment Act (ARRA). These discontinuities in funding levels since 1985 provide opportunities to descriptively explore, and potentially isolate, the impacts of the qualitative shift in funding regimes that occurred during the doubling period.

The NIH doubling period coincided with great excitement in the scientific community. The human genome had recently been mapped, and there was a general feeling that the time was "a golden age of discovery, one unique in human history" (National Cancer Institute Director, Richard D. Klausner quoted in (Pear 1998)). Priorities were set in this context with a dual emphasis on research and policy, with the NIH Director asking "What are the scientific opportunities, and what are the public health needs?" (Harold E. Varmus quoted in (Pear 1998)). Reflecting on the doubling period after it ended, former NIH Director Elias (Zerhouni 2006):1088) noted that the doubling period led to an "unprecedented expansion of research capacity across the country that began in 1999" and that this resulted in "the development of entirely new fields of research, leading to an acceleration of the pace of promising research advances across the biomedical and behavioral sciences." The goals of the doubling were ambitious, even revolutionary.

Were these goals met? One can see growth in the numbers of U.S. based biomedical publications indexed by ISI Web of Science over this period, but there are no meaningful differences in growth rates between publications tagged as being based in the United States versus other countries, and there is no corresponding decline after the doubling period ended

(Sachs 2007). It is worth asking if we would expect a decline, however, as the doubling expanded scientific capacities and funding levels remained high after it abated. Without explicit reference to the doubling period but using more rigorous panel and instrumental variable methods of analysis that seek to isolate causal effects, examinations of productivity changes in authors and research institutions receiving NIH funding have tended to find modest effects on the order of 0.4-1 additional publications over a five year period for each additional research grant awarded to individual researchers and 11-19 additional publications in the year after funding is awarded for each $1 million awarded to universities (Adams and Griliches 1998; Jacob and Lefgren 2011; Payne and Siow 2003; Rosenbloom et al. 2014; Whalley and Hicks 2014). Because the doubling enabled the NIH to fund more grants at larger values, these findings suggest an impact, at least in terms of increased publications and successful research translation.

However, I assert that research translation is an insufficient metric for quantifying revolutionary scientific advancements because trends in counts of publications and research translation are driven by a multitude of factors, including secular global increases in life expectancy and venues for publication. The question remains: did the NIH doubling period alter the direction of research in any significant way or simply increase the amount of research being conducted? In addition, it is worth asking whether, in the post-doubling period, the enhanced research capacity of American bio-behavioral scientific institutions claimed by NIH Directors and other policy makers and the overall higher levels of funding and awards have been enough to maintain the innovation and scientific breakthroughs that were promised, a reason to suspect an impact, or else whether the real dollar decline and slight decrease in numbers of new awards since 2003 eroded any potential progress that was made during the doubling period.

The sociology of science literature suggests that we should look to the idea space of research to understand whether the NIH doubling period achieved its goals (Weitzman 1996, 1998; Shwed and Bearman 2010). The idea space of scientific research consists of all ideas pertaining to "research questions, methods, and implicit rules for evaluating evidence" and, importantly, the relationships within and between these entities (Moody 2004). An important feature of idea spaces is that they are dynamic and change over time both in terms of composition – some ideas emerge and gain attention, while others are forgotten or ignored – and in terms of topology – which ideas are held in combination to form knowledge versus which are considered distinct and far apart (Olsson 2000). The compositional approach to idea spaces has been most thoroughly studied in the topic modeling tradition (Blei 2004; Blei and Lafferty 2006; Talley et al. 2011), which has shown substantial changes over time in the amount of research dedicated to specific research topics, like atomic physics or neuroscience. If the NIH doubling period led to a revolution in the idea space of biomedical research, we might expect an increase in novel combinations of ideas consistent with the potential for "recombinant innovation" (Weitzman 1996; Weitzman 1998). Prior work has demonstrated that papers which exhibit novel integration of pairs of subfields within a single discipline have higher levels of citation than those which do not integrate across subfields (Leahey and Moody 2014). More generally, other work has found that papers which combine citations to unexpected pairs of journals are more highly cited and that chemists who research new combinations of chemicals are more likely to win prestigious awards (Foster, Rzhetsky, and Evans 2013; Uzzi et al. 2013). These findings reinforce my choice of focus, but I look much earlier in the research process, when projects are initially proposed and funded.

Many believe that the NIH review processes favor incremental science[1]. Looking at

[1] See e.g., comments in online NIH discussion forums (e.g., http://nexus.od.nih.gov/all/2013/11/14/dispelling-

research on the plant model *Arabidopsis thaliana*, Evans (2010:397) found that federal funding of research leads to more "methodologically conservative, confirmatory science" because the peer review process selects on ideas that are likely to work and which have been applied in the past. He argues that "[f]ed with grants dispensed by their peers, university scientists have been increasingly constrained to follow established currents in science" (Evans 2010:390). With more money available, the NIH may have had more leeway to fund riskier projects. Similarly, the increased pool of research money may have attracted riskier research proposals from applicants with prior NIH experience, or it may have expanded the pool of applicants to include a broader array of scientists and expertise. The reverse logic is also possible: scientists seeking to quickly gain access to the extensive resources made available as a result of the doubling might have committed to further research on well-trodden ideas. Another alternative is that the increased budget allowed the funding of weaker applications, which would not be expected to lead to breakthroughs. Li and Agha (2015) find that the NIH peer review process works well at predicting the future impact of a grant in terms of its resultant publications and patents and their citations. Whichever may be, in the end, what is important is the science that was undertaken. Did the NIH doubling period change the novelty of funded research projects?

Changes in the idea space of scientific knowledge extend beyond novel pairwise combinations, however, as they can also manifest in larger units of aggregation. Shwed and Bearman (2010) look at the accuracy by which citation networks can be clustered into aggregate clusters – called communities (Porter, Onnela, and Mucha 2009) – to measure the emergence of consensus on contested research topics, arguing that consensus increases as the accuracy with

rumors-on-nih-application-limits/, http://nexus.od.nih.gov/all/2013/12/18/application-success-rates-decline-in-2013/, http://loop.nigms.nih.gov/2014/03/hypothesis-overdrive/comment-page-1/).

which communities overlap with networks formed from co-cited articles decreases. Bruggeman, Traag, and Uitermark (2012) challenge their methods, however, and argue that repeated cross-sectional examination of citation networks– to the neglect of shifts in the content of the research conducted and adversarial citations – yields incorrect conclusions. Nonetheless, the idea that shifts in the idea space can be captured by macro-structural *relational* changes in the organization of a network of ideas is a powerful one that expands on *compositional* questions about changes in what is being researched over time. Taking a dynamic network approach to the idea space of funded biomedical research proposals in this fashion provides an opportunity to examine both the share of research being conducted on sets of ideas in a given year and the relative alignment of ideas vis-à-vis one another. By tying such changes to specific grants funded at specific points in time through an analysis of idea spaces as revealed through application abstracts, I capture dynamics in the relational dimensions of the idea space of knowledge. If the NIH doubling period achieved its purpose, we would expect to see fundamental shifts in the macro-structural characteristics of the idea space during or shortly after the doubling period commenced. While longer lags might be expected for aspects of research translation (e.g., mortality rates, patents, citations, and even publications), the work that is being proposed and funded should be more rapidly responsive to the change in funding regime, although there may still be a lag.

Approach, Data, Measures, and Methods

Figure 2.2 portrays three hypothetical scenarios that showcase different types of effects the NIH doubling period may have had on the ecosystem of scientific research. The y-axis is labeled as innovation in this graph as I intend these change scenarios to be general and applicable to a variety of outcomes of interest with respect to the NIH doubling. Whereas prior work has populated this axis with publication and citation counts, I populate it with network measures discussed below. The line labeled A is a case where the NIH doubling appears to have had a clear effect; the statistic of interest fluctuates slightly during the pre-doubling period, but begins a steep upward shift as the doubling commences. Of course, it is not possible to isolate the doubling as a cause of this change based solely on a temporal analysis, but the fact that the change in trajectory is coincident with the onset of the doubling period would provide suggestive evidence. The line labeled B is a case where the doubling does not appear to have had an impact. In this case, the statistic remains virtually unchanged over the whole period. Finally, the line labeled C provides a third hypothetical case. Here, there is a clear increase from the doubling onward, but this increase appears to simply be the continuation of a long-standing trend from the pre-doubling period. There may also be in-between cases, described in more detail below.

I explore the doubling period's impacts on the idea space of scientific research by descriptively analyzing trends over time. One critical area of concern in this analysis pertains to lagged effects. It is possible that the NIH doubling period's effects did not manifest immediately. For instance, (Manton et al. 2009) show that age-adjusted death rates for diseases studied by specific NIH institutes closely track decade-long lags in funding for those institutes, but that they do not appear to follow contemporaneous funding levels. Leahey and Moody (2014) show that novel work is more likely to be cited and have an impact over a longer horizon. However, I do not expect that lags in the types of research being funded and conducted would be on the order of decades given the data source. Looking at citations to papers, others have used an 8 year post-publication window to assess impact (Uzzi et al. 2013), which is comparable to potential 10 year window of data I observe after the doubling began. Research proposals typically take 2-3 years before they are funded, and even longer until the research is completed and results are published, then cited. Based on these time frames, we might suspect that impacts of the doubling would be seen more quickly than the time windows for publications and citations. Despite the 2-3 year lag before funding, the doubling may still have an immediate impact if it changes the type of research being chosen for funding by NIH, rather than changing the types of research proposed or the types of people making research proposals. I suspect that impacts of the doubling will be seen during the ten year period from 1997-2007.

I use data drawn from the National Institutes of Health's (NIH) RePORTER database made available through the ExPORTER system (http://exporter.nih.gov). This source includes abstracts for every funded grant awarded from 1985-2013 (for reasons discussed below, I focus only on funded proposals up until 2008). I argue that grant applications in their first year of funding represent the leading edge of scientific research that is being conducted at a given point in time and are more comparable across fields than other research outputs, which may have field-specific lag times. The 1,671,601 funded grant applications in this database cover a broad swath of American bio-medical research that has been funded over the past 29 years, which provides the opportunity to examine research trends in American science, at least a substantial corner of it, which have heretofore been underexplored. Importantly, the database does not contain intramural NIH projects, only external awards. I retained only the 549,850 abstracts which were new applications or competing continuations, renewals, revisions, extensions, and administrative supplements (i.e., I did not retain non-competing continuations or changes of grantee institution or awarding Institute or Division within NIH). Other types of applications are difficult to tie to a specific year of initial funding (e.g., non-competing awards). Tying applications to the specific years in which they are first funded is a critical portion of my analysis because of my focus on trends over time. I only focus on applications which were actually funded – the database does not contain proposed but unfunded applications. However, funded applications are more likely to be carried into actual research, which I assert will yield a better representation of the pursuit of scientific knowledge than an analysis based on unfunded proposals. Also, I am interested in the doubling – i.e., funding. Of course, it is possible that those who are unsuccessful take their novel ideas to a different sponsor, federal or otherwise – in other words, there may have been indirect effects of the NIH doubling period on scientific research – but that is beyond the scope of what I can investigate in this chapter. By excluding intramural projects and non-competing awards, I can focus on how the NIH budget doubling directly affected the trajectory of American biomedical research.

Figure 2.3 highlights some important features of the data used in this paper. The line with the short dashes shows the total number of applications funded per year over this period, while the dotted line shows those which were competing applications. The number of total funded applications was variable but steady from 1985-1995, then increased substantially until 2000, at which point a slow decline ensued, which was broken only by a massive spike owing to the availability of ARRA funding. A similar, but more muted trajectory can be seen for competing applications. This trajectory presents an interesting contrast to Figure 2.1, which showed funding levels, because it clarifies a) that prior to the doubling period the number of competing applications that were funded varied considerably from year to year, b) that the doubling period was preceded by a ramping up in the number of new applications that were funded perhaps in anticipation of the doubling, and c) that the number of new applications began declining prior to the end of the doubling period. Former NIH director Elias (Zerhouni 2006) attributed these discrepancies to infrastructural investments on the part of the NIH, increases in award sizes, and residual commitments to multi-year projects; in other words, the doubling of the budget did not translate directly to a doubling in the number of awards.

The third line in Figure 2.3, the dashed line, shows the number of funded grants and contracts whose abstracts contain keywords. In total, there are 398,341 abstracts with keywords across all years of data. These are critical to the analyses in this paper. Though the coverage of grants with keywords slightly improves over time (i.e., the rate of missingness declines), the general trends in the numbers of proposals with keywords mimics what is seen in the total numbers of items seen in the entire data set. A supplemental analysis of these missingness patterns, shown in the appendix Figures 2.A1 and 2.A2, explores whether certain types of grant mechanisms (e.g., "R"-grants vs. "U"-grants) or funding institutes (e.g., National Cancer Institute vs. National Institute of Mental Health) are disproportionately missing keywords. This analysis showed relatively consistent rates of missingness amongst grants administered by the major NIH institutes (i.e., those with "Institute" in their name), while grants administered by more minor centers tend to be missing at much higher rates. In addition, the important research grants ("R" and "P") are well represented while those funded under other mechanisms tend to be missing more often. Given the focus of this paper on the doubling's impact on research, it is important that the research grants are well represented.

I focus on the keywords that NIH assigns to funded proposals, which are referred to by the NIH as project terms; more information on how NIH assigns terms to a project can be found online (http://www.nlm.nih.gov/research/umls/sourcereleasedocs/current/CSP/). NIH changed their method of keyword assignment in 2008, so I do not focus on grants funded from that date on. The 25 most common keywords in the data set and their frequencies over the study period are shown in Table 2.1. The most common keywords are those we would expect, speaking to broad areas of interest (e.g., "human subject", "gene expression") and core methodologies ("laboratory mouse", "longitudinal human study"). I drop any keywords used only once throughout the study period, which causes 10,262 applications to drop out leaving a final sample size of 388,079.

To analyze these data, I use dynamic network methods (Mucha et al. 2010). I construct networks of keywords where links between keywords exist if they co-occur in the same funded grant and where the links are weighted by the number of co-occurrences for that pair across all grants in the data set. In a first set of analyses, I define repeated cross-sections of the network of keywords. Here, I focus on the novelty of keyword combinations used in a given year. For each year t, I define the novelty of the combination of keyword i with keyword j as $novelty_{ijt} = \ln(\frac{e_{ijt}}{o_{ijt}})$, where o_{ijt} is the observed number of grants in which keywords i and j co-occur in year t, and e_{ijt} is the expected number of grants that they would co-occur in under conditions of independence; i.e., $e_{ijt} = \left(\sum o_{it} \sum o_{jt}\right)/\sum o_{ijt}$. A similar approach defining novelty across all years showed almost identical patterns (not shown). This measure is similar to others used in the networks literature (Leahey and Moody 2014; Schilling and Green 2011; Uzzi et al. 2013; Foster, Rzhetsky, and Evans 2013). It is distributed such that higher values – i.e., those which occur closer to or less frequently than the expected rate – reflect greater novelty. Only keywords that occur in a given year are used in the construction of the annual novelty measures. In other words, the higher the novelty score, the more novel the combination.

The most novel combinations in the data analyzed are those where each of the constituent keywords occurs in many grants in a given year, but the pair of them tend to occur in relatively few. In the data analyzed, the most novel combinations of keywords tend to be those which combine terms used frequently in the pre-clinical bench sciences (i.e., "laboratory mouse") with terms used frequently in the clinical sciences ("e.g., longitudinal human study") but which are rarely used in conjunction.

Figure 2.4 shows a network map of the well-connected portion of the idea space in 1997, just before the doubling begins. Each node in the network is a keyword, while edges are shown between two keywords if they co-occur in more than 60 funded applications (the graph is plotted on the basis of edges that co-occur in more than 10 applications, but edges were only rendered in the more restrictive case to make visualization simpler). I restricted the presentation to the largest connected component of the network on the basis of edges that co-occur in more than 10 applications; this encompassed 2,830 of the 7,628 keywords used in this year (37.1%). The top 10 most commonly used keywords are labeled. There are two large clusters of keywords. On the bottom left of the figure is a cluster of keywords related to the clinical sciences (e.g., "human subjects"), while on the top right of the figure is a cluster of keywords pertaining to the preclinical sciences (e.g., "nucleic acid sequence"). There are a substantial number of links between these clusters, as well as links from both to smaller clusters outside of this dominant division. The most novel applications are those which bridge these large clusters.

For instance, consider the application whose keyword combinations are shown in Table 2.2. This application has somewhat high novelty, but only five keywords. There are 20 possible combinations of these keywords, few of which are novel. Indeed, only the top decile of this application's keyword combinations take on positive values on the novelty scale (both combinations of "biomedical facility" with "transcription factor" and "genetic regulation"). As such, most applications will score low on the novelty scale, and it is likely that much of the distribution of application level novelty will be negative.

To assess whether the doubling had an impact on the idea space of scientific research, I first consider Figure 2.5 which parallels Figure 2.4 in style, but shows the network map of keywords in 2004, just after the doubling ended. There is a great deal of similarity between the two figures: many of the same keywords appear and the same two core clusters – clinical sciences on the left and pre-clinical sciences on the right – can be seen. This is to be expected however, given that these figures focus on the core of the keyword co-occurrences network that are the most densely linked (remember, only edges which co-occurred in more than 10 funded applications were used to plot the layout of nodes in these figures). The differences between the figures are subtle, but important. One of the clearest is the greater density of nodes in Figure 2.5 compared to Figure 2.4. This is because a larger percentage of keywords are linked into the largest connected component in 2004 than were so linked in 1997. In 2004, there were 7,887 keywords used and 3,111 of them were in the largest connected component (39.44%), which compares favorably to the 1997 percentage of 37.1% on a slightly smaller denominator. There is also a greater density of edges in the 2004 data, making the clusters tighter and the area between them more traversed. Together, if they generalize to a broader trend, these results would suggest that the doubling period increased novelty because there are more connections between keywords and more connections between disparate clusters of keywords, which means that keywords that were not frequently used together in 1997 tended to more frequently co-occur in a larger number of grants in 2004. Of course, it is challenging to generalize these network graphs to a larger number of years. This is my motivation for turning to summary measures.

To develop a measure of novelty of applications, I take the median and the 90th percentile of each application's novelty combinations. These measures parallel the concepts of "median conventionality" and "tail novelty" put forth in prior work on the basis of atypical combinations of journal citations, and, at the level of published papers, they have been related to the "hit rate" or likelihood of being highly cited in the literature (Uzzi et al. 2013). By considering both of these metrics, I can assess whether the NIH doubling period affected the overall scope of proposals (median novelty), whether it affected the incorporation of risky ideas into proposals (tail novelty), or both.

I am also interested in whether the doubling affected all funded applications equally, or whether its influence was concentrated amongst the most or least novel applications in a given year. In each year, there are many proposals which are funded, creating annual distributions of median and tail novelty. To look at how these distributions may have shifted in response to the doubling, I focus on the key quantiles: 5th percentile, 25th percentile, median, 75th percentile, and 95th percentile.

After exploring novelty, I shift focus. Up to this point, I have focused on applications as the unit of analysis. The next set of analyses examines the co-occurrence network of keywords. I am interested in how the doubling may have affected the entire system of ideas, particularly the emergence of new clusters of research activity and changes in the organization of extant clusters overall. I consider larger, macro-structural groupings of keywords that correspond to clusters of research activity. To do this, I apply recent insights (Bruggeman, Traag, and Uitermark 2012; Shwed and Bearman 2010) and use a community detection approach (for a review of community detection, see (Porter, Onnela, and Mucha 2009)). In a network, a community is defined as "a subset of a larger population where internal ties are more prevalent than ties to other subsets" (Shwed and Bearman 2010). Any network can be partitioned into many different sets of communities, but there are explicit algorithms that find well-fitting partitions that maximize the ratio of in-community ties to between-community ties, a process known generally as community detection; I use the Louvain method (Blondel et al. 2008). A key issue in community detection is that the researcher must choose a resolution parameter which governs the size of the communities that will be found, and, correspondingly, the number of communities. While community detection is often used on snapshots of network ties, recently developed methods, which were championed in Bruggeman et al.'s critique of Shwed and Bearman, allow researchers to define communities that partition the network in idea space as well as time through the introduction of a coupling parameter which governs the tendency for items of interest to be assigned to the same community over time (Mucha et al. 2010). I use this "multi-slice" or multilayer community detection approach with resolution and coupling parameters of 0.5, though I have tested the sensitivity of my results to different specifications of these parameters using the generalized Louvain code available online (Jutla, Jeub, and Mucha 2012).

I am interested in shifts in clusters of research activity, particularly changes in their sizes and the emergence of new clusters. I create annual networks of keywords based on their co-occurrences in applications. I then use the longitudinal community detection approach to partition them into communities in each year. Of interest is whether the community structure of the network changed dramatically in response to the doubling. To understand how the doubling affected the idea space of federally funded biomedical research, I examine the longitudinal community detection results through sequence plots (Kohler and Brzinsky-Fay 2005; Scherer 2001). Sequence plots show which community each keyword was assigned to at each point in time. These sequence graphs allow me to track the entire system of ideas as grouped into coherent clusters of research activity. The graphs are similar to heat-maps, with a horizontal line for each keyword. At each year in the data, keywords' community assignments are color coded. Keywords are arrayed along the vertical axis so that groups of keywords that persist in the same community are kept together, while those that split off of them into separate communities at each point in time are grouped until they too split. I also consider the number of keywords changing communities in each year. If the doubling had a large impact on the macro-structural organization of keywords, then after it commences I would expect a marked change in community assignments of keywords. This should be visually apparent in the sequence plot, but should also be viewable when looking at the subplot showing the number of keywords that change communities in each year. A final consideration from the community detection approach is whether new communities emerge after the doubling period ceases. This would be evident in the emergence of new groups that had low levels of representation in the idea space prior to the doubling.

Results

Did the NIH doubling revolutionize biomedical science? I first look at whether the novelty of funded grant applications changed in response to the doubling. I operationalize the novelty of a grant application on the basis of its keyword combinations. This measure captures the unexpectedness with which ideas are combined in the application. For instance, a novel application might be one that combines ideas from the clinical sciences and the preclinical sciences, which tend to be used together rarely as shown in Figures 2.4 and 2.5, while a conventional application is one whose keyword combinations are frequently used together. After looking for changes in novelty at the application level, I examine the entire system of ideas. To do this, I use a longitudinal community detection approach that finds temporally coherent large-scale groupings of keywords on the basis of their co-occurrence in grant applications.

Figure 2.6 shows quantiles of the distribution of median novelty scores, plotted with lines connected across years rather than as box-plots to facilitate the visual detection of changes. There is a clear break in the median novelty scores for the 25th and larger percentiles at the onset of the doubling in 1998. This change is, however, short-lived. All points revert back to near but still slightly above their pre-doubling levels by 2000. After the doubling, they rise again dramatically in 2005 and remain high heading into 2008. The lowest quantiles of the median novelty distributions, the 5th percentile and to some extent the 25th percentile, show more secular trends, with both rising slowly over the entire series. The clear and compelling change in the distribution of novelty scores is statistically significant, as these distributions contain tens of thousands of funded applications in each year and are based on millions of keyword combinations. There is a two unit change on the novelty scale in some cases. In the pre-doubling period, a two unit change was the difference between the 25th and 95th percentile of application-level novelty, so this change at the onset of the doubling is very large. Figure 2.7 shows a very similar set of changes for tail novelty. Even here, there are few applications which have more than 10% of their keyword combinations taking on positive values on the novelty scale. The changes in median and tail novelty suggest a dramatic response to the doubling wherein authors in 1998 applied with or NIH funded entirely new ideas as the doubling was announced, but then retreated from these changes in subsequent years. It was not until 2005 that a similar surge in novelty was observed.

Next, I turn to an analysis of the dynamic community structure of keywords used in NIH grants. Figure 2.8 shows a sequence plot of the communities of keywords and an overlaid line graph which shows the number of keywords that change community assignment. The doubling period, 1998-2003, is boxed in black. Each point along the left y-axis is a keyword and the colors indicate the communities into which keywords were assigned in each year (ordered along the x-axis). The right y-axis shows the number of keyword changes in each year and corresponds to the dashed line. The multi-slice community detection algorithm (Mucha et al. 2010) with the resolution and coupling parameters set to 0.5 found four communities in the longitudinal NIH keyword co-occurrence network: they are shown here with blue, red, green, and orange colors. In the 1980s and early- to mid-1990s, there were primarily two communities of keywords which each had roughly half of all the keywords. These are shown in red and blue (a third community, shown in green, had very few keywords assigned to it during this period). The center of the graph shows the trading of keywords between these stable communities, where some keywords assigned to the red community switch to blue and vice-versa, as well as switching back. The number of keywords switching community assignments in each year over this period is generally stable (the initial rise in this line is somewhat misleading since, by definition, no keywords can switch communities in the first year of the series). An investigation of the most frequently occurring keywords in these groups indicates that these communities could be characterized as research in the clinical and pre-clinical traditions, as would be expected on the basis of Figures 2.4 and 2.5.

A remarkable change occurs shortly after the doubling commences, however. In 1999, almost all of the keywords assigned to the red community become assigned to the green community, which until that point had captured a marginal portion of the network. The number of community switches in this year rises to triple the rate seen in years prior. That this shift occurs shortly after the doubling commenced is consistent with the idea that the doubling period changed science. Something very substantial happened in the way in which keywords were used together in NIH grants shortly after the doubling commenced, though it is unclear from this graph exactly what. There is a final point of interest in this graph: the emergence of the orange community in the early 2000s which largely split off of the green community. This community did not exist prior to that point. This suggests that a new field of research emerged as a lagged result of the changes brought about by the doubling.

Table 2.3 shows the 20 most commonly used keywords tagged as being part of the orange community after the doubling. Many of these are related to cancer and genomics terms (e.g., “virus rna”, “deoxyribopolynucleotide”. The emergence of this community showcases the new ways of studying cancer that emerged after the doubling period ended. As can be seen in Figure 2.8, this community did not exist prior to 2005, but it gained prominence after the doubling ended. It is important to remember that the Human Genome Project announced a complete sequencing of the human genome in 2003, corresponding with the ending of the doubling period. After this, new research topics like the one shown in orange in Figure 2.8 emerged.

Discussion and Conclusions

I asked whether the NIH doubling period achieved its goals of revolutionizing science. Prior assessments of this topic have tended to focus on easily measurable research outputs like publications or else on case studies of successful innovations that are challenging to generalize, but they have neglected the sociology of science literature which suggests that to understand scientific revolutions we must look at the structure of knowledge itself. I apply the concept of a dynamic, topological idea space to funded competing NIH applications from 1985-2008 to assess, through an interrupted time-series design, whether the NIH doubling period coincided with substantial changes in how ideas are researched.

I measured the idea space in two ways. First, I looked at a measure of the potential for recombinant innovation derived from repeated cross sections of the network of keyword co-occurrences. Aggregating this to the level of funded applications, I analyzed the successful integration of atypical research topics. I looked at two measures, median and tail novelty. These measures reflect the novelty with which an application combines keywords on average as well as whether the application contains some injection of high novelty regardless if the proposal, on the whole, is conventional. Looking at the distribution of these measures over time, I found a substantial shift in both of them at the onset of the NIH doubling period. For a short period after the doubling commenced, funded applications contained more novel combinations of keywords. However, this initial influx of novelty did not last long, as the tendency of these distributions reverted back to pre-doubling novelty levels after 1998. This reversion was truer for tail novelty than for median novelty, suggesting that the doubling may have slightly increased novelty of all proposals, but that it did not have a lasting impact on the most novel combinations of ideas.

Second, I measured the idea space of funded research using a longitudinal community detection approach. This analysis showed a very substantial change in the community structure of the NIH keyword network beginning just after the doubling began. Before the doubling, there were two dominant clusters of research that can be summarized as the pre-clinical bench sciences and the clinical sciences. Most keywords were linked to one or the other of these clusters and, while there were links between them, they were rarer than links within the clusters. Some keywords drifted between the two clusters over time, changing membership, but there was a general stability to this system. Beginning in 1998, at the onset of the doubling, however, something radical happened as one of the clusters was completely reoriented toward other ideas. This analysis also highlighted the subsequent, though still nascent, development of new fields of research after the doubling ended. Many of these fields represent the proliferation of genomics based research after the Human Genome Project announced its partial and complete mapping of the genome in 1998 and 2003. Looking at the network graphs in Figures 2.4 and 2.5 before and after the doubling, we can see the closer integration of genomics research with the preclinical sciences over the course of the doubling. Closer examination of these patterns is a fruitful avenue to pursue in future research.

Future work on this topic could seek to address issues of causality. Though the interrupted time-series design provides suggestive evidence of causal effects, more leverage can be gained. Future work can build on the approach used by Manton et al. (2009) to separate out these changes by NIH institute and assessing whether grants administered by that institute were more or less likely to exhibit changes. Ideally, this analysis would incorporate the time series of funding levels by institute. By introducing this additional layer of heterogeneity, an analysis that examines changes over time and across institutes would provide the opportunity to make stronger, if not definitive, causal claims. This analysis also has the potential to shed additional light on how the changes observed so far occurred. One hypothesis is that much of the additional funding from the doubling went to the National Cancer Institute (eradicating cancer was mentioned in Clinton's State of the Union Speech) and that the genomics revolution was most concentrated in cancer research. Whatever the case, this analysis will clarify the mechanisms by which the doubling affected science. Other questions to be addressed include whether the doubling achieved its mission by funding more novel research, enabling more novel research through infrastructural investments, or altering the pool of researchers applying for NIH grants. An additional analysis could focus on indirect effects, examining whether the doubling had spillover effects on the novelty of research pursued in grants funded by other federal agencies.

In sum, in this chapter I have advocated for a more nuanced understanding of the effects of public research funding on scientific activity. While there is a benefit to measuring numbers of publications, patents and citations, it is also important to understand how ideas are being researched. I argue that a dynamic networks approach to idea space can facilitate this and demonstrate how these methods can help us to understand a substantial national event. Can federal funding buy a scientific revolution? Based on this research, I conclude that the doubling of the NIH budget did achieve its goals of funding a scientific revolution, but not in the most easily measurable ways. I have shown that the onset of the doubling coincided with a substantial increase in the novelty of funded grant applications as well as a significant shift in the ways in which keywords were used in funded applications, representing a shift in the idea space of biomedical research. Examination of what changed in the use of keywords suggests that the fuller incorporation of genomics research into the preclinical sciences occurred at the same time as the doubling. Whether these patterns can be repeated, however, is an open question.

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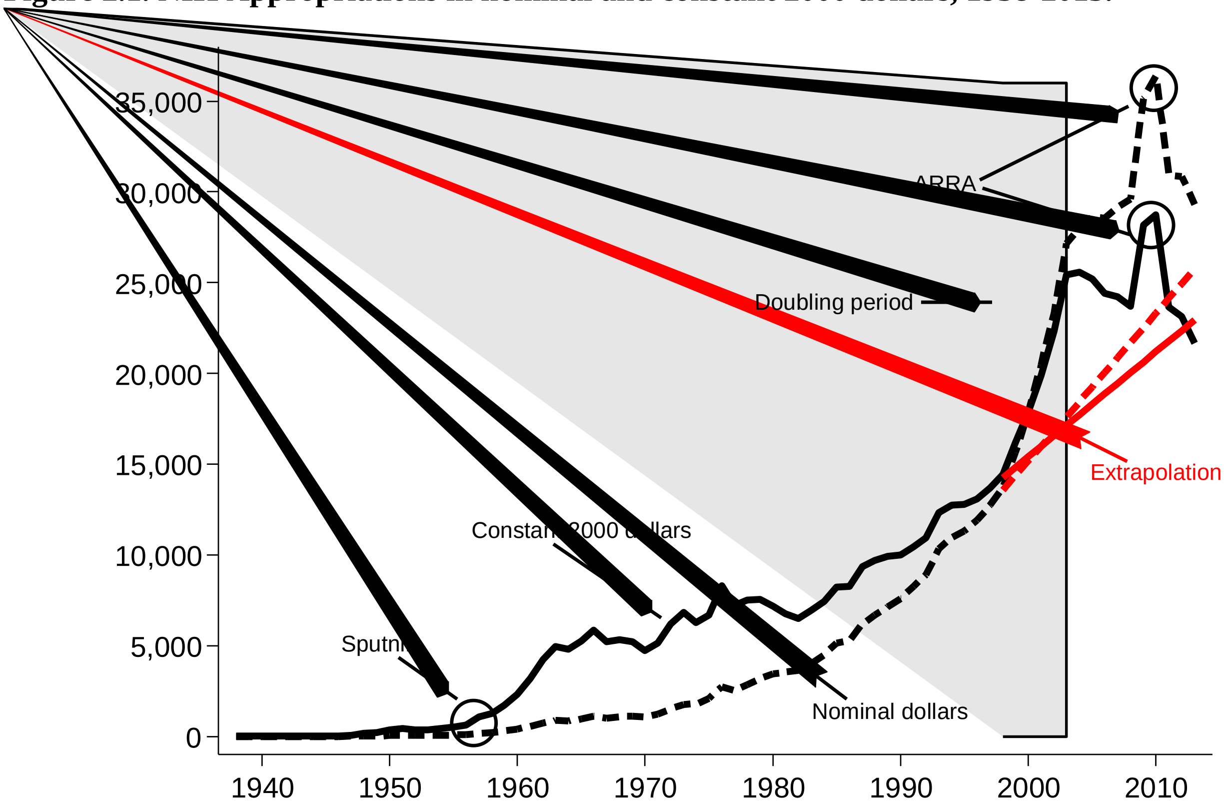
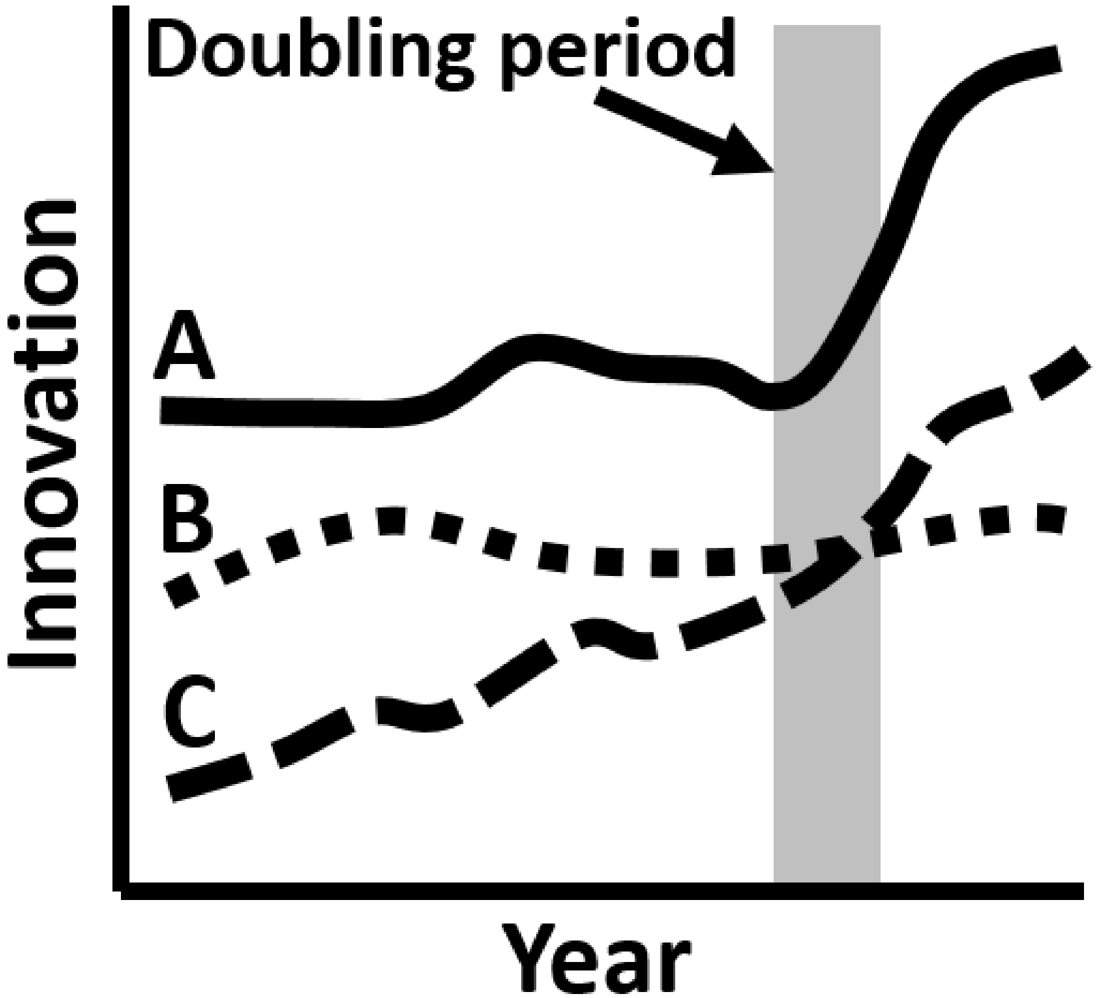
Figure 2.1. NIH Appropriations in nominal and constant 2000 dollars, 1938-2013.



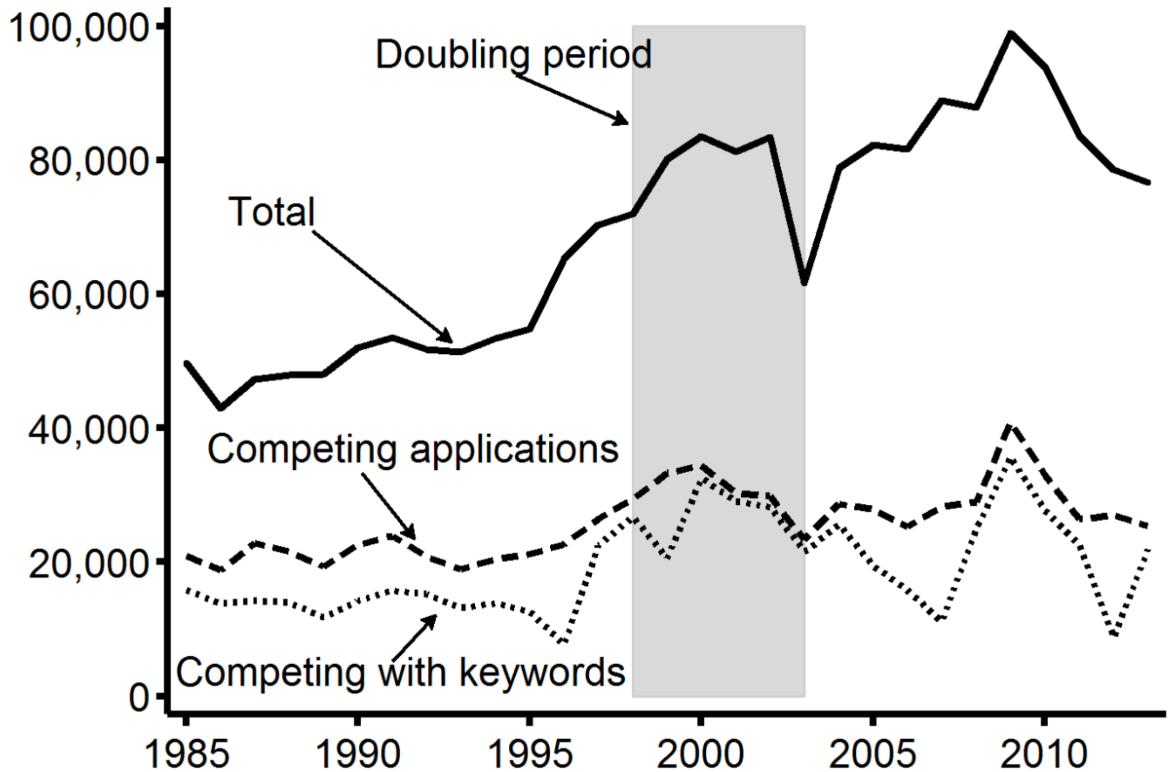
Notes. Data drawn from http://www.nih.gov/about/almanac/appropriations/part2.htm, accessed 6/9/2014. Data for 2009-2010 includes ARRA Supplement funding reported in Johnson, Judith A. "Brief History of NIH Funding: Fact Sheet". Congressional Research Services Report, R43341. Table 1. Page 4. Constant 2000 dollars are adjusted by the Biomedical Research and Development Price Index (BRDPI). In nominal dollars, appropriations increased 147.4% from 1985-1997, 98.7% from 1998-2003, and 4.6% from 2004-2013. In constant 2000 dollars, they rose 50.9% from 1985-1997 and 68.0% from 1998-2003, and they fell 21.3% from 2004-2013. The expanded funding levels in 2009 and 2010 owe to the American Recovery and Reinvestment (ARRA). Red lines show the linear extrapolation of the pre-doubling trends.

Figure 2.2. Schematic of hypothetical changes associated with the doubling period.



Notes: Line A is interpreted as being consistent with the doubling having an impact, whereas lines B and C do not.

Figure 2.3. Trends in funded NIH applications used in this paper, 1985-2013.



Notes: Data are drawn from http://exporter.nih.gov/about.aspx, accessed 6/8/2014. Data for 2009-2010 includes ARRA Supplement grants. Only competing grants with available keywords are analyzed in this paper.

Figure 2.4. Map of the largest connected component of keyword co-occurrences just prior to the doubling, in 1997, with the top 10 most commonly used keywords labeled and highest weighted edges shown.

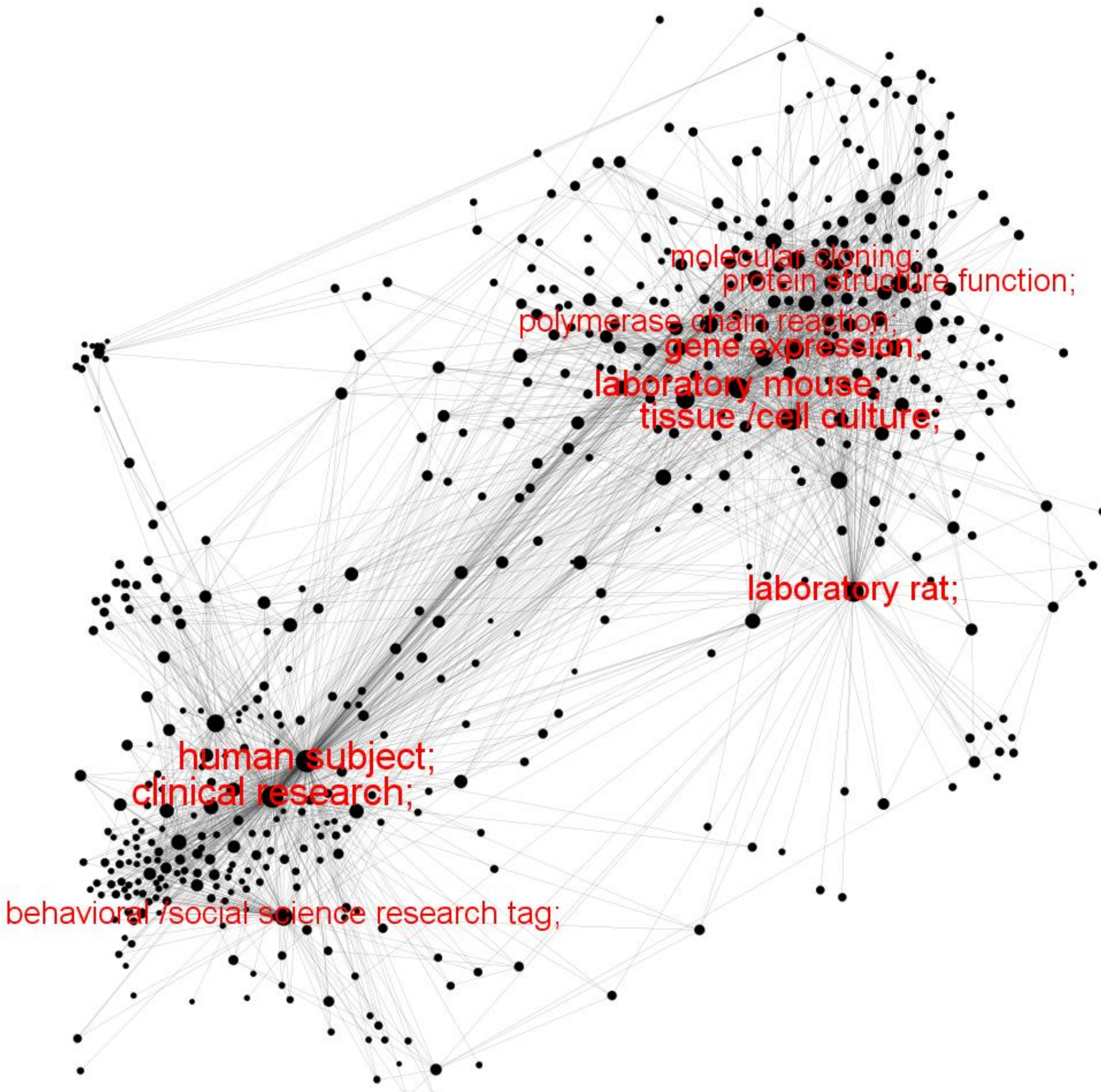


Figure 2.5. Map of the largest connected component of keyword co-occurrences just after the doubling, in 2004, with the top 10 most commonly used keywords labeled and highest weighted edges shown.

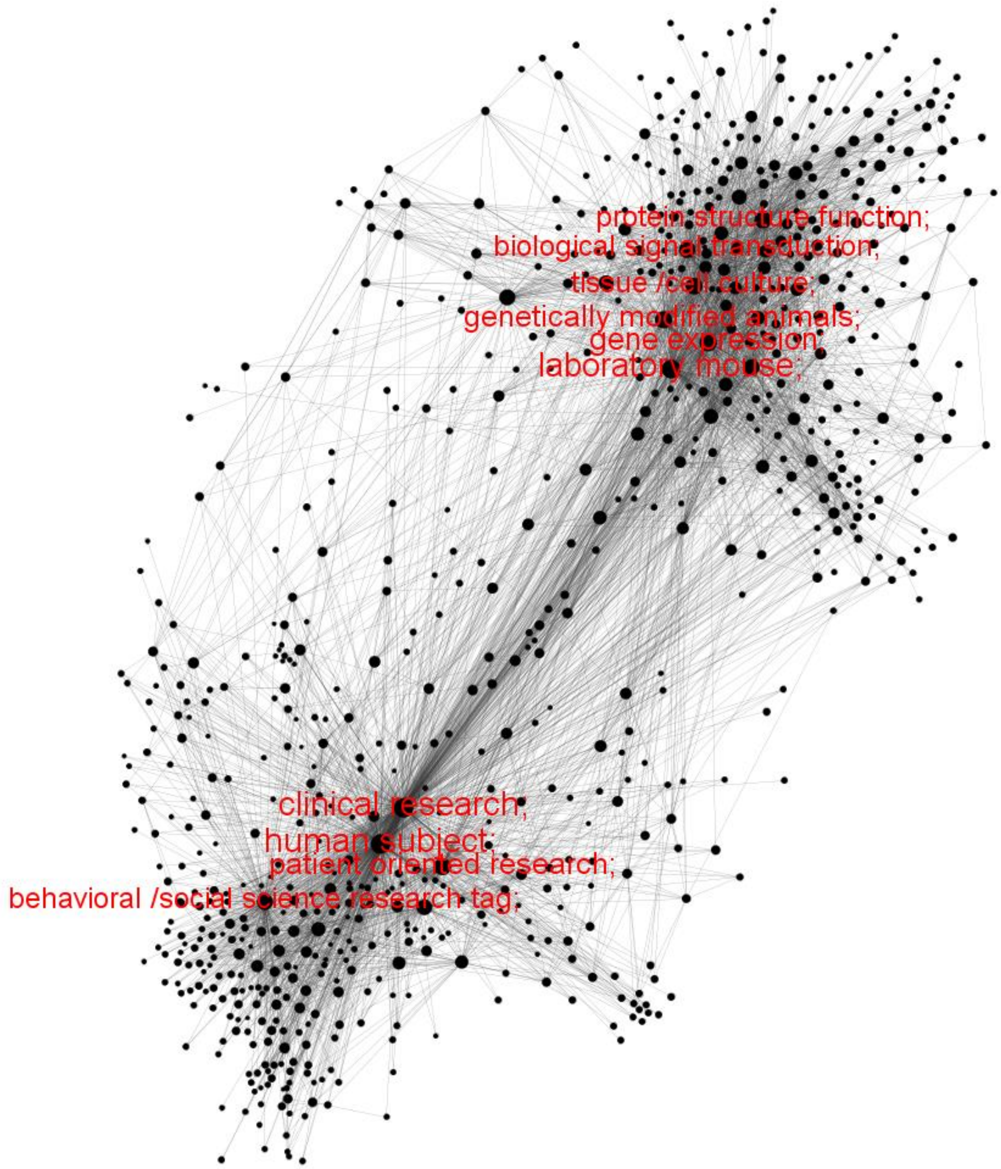
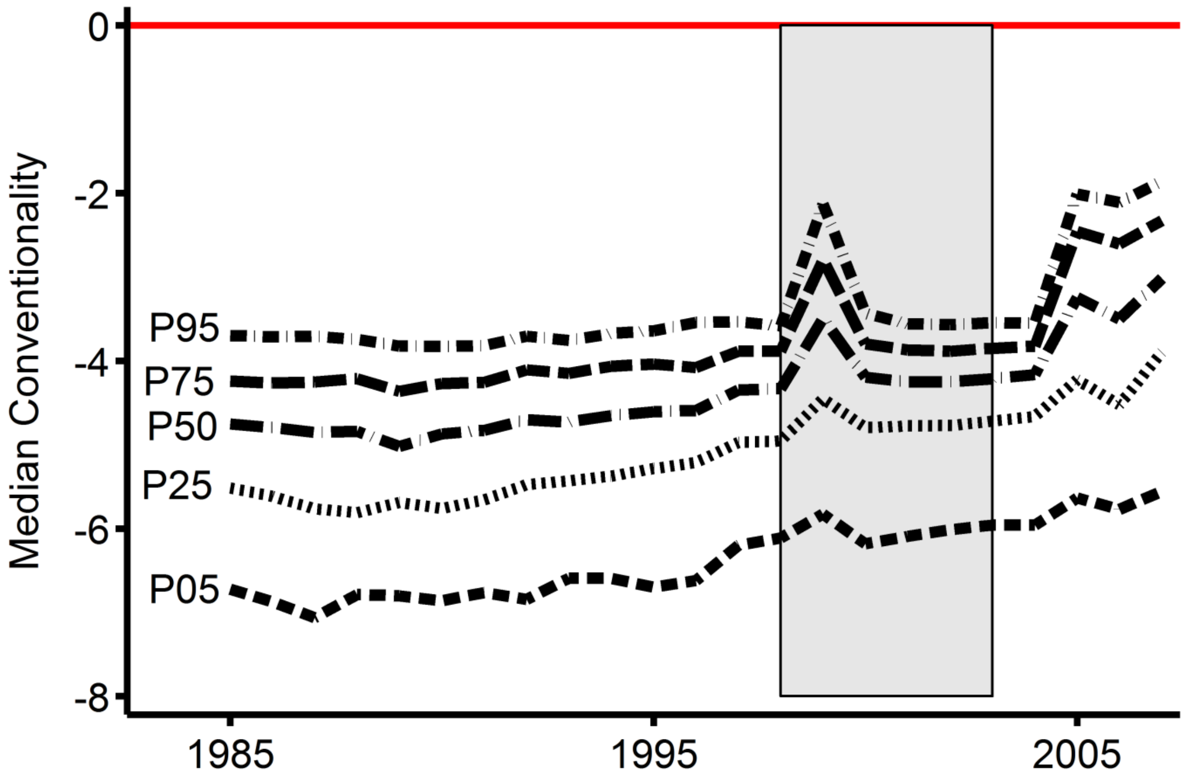
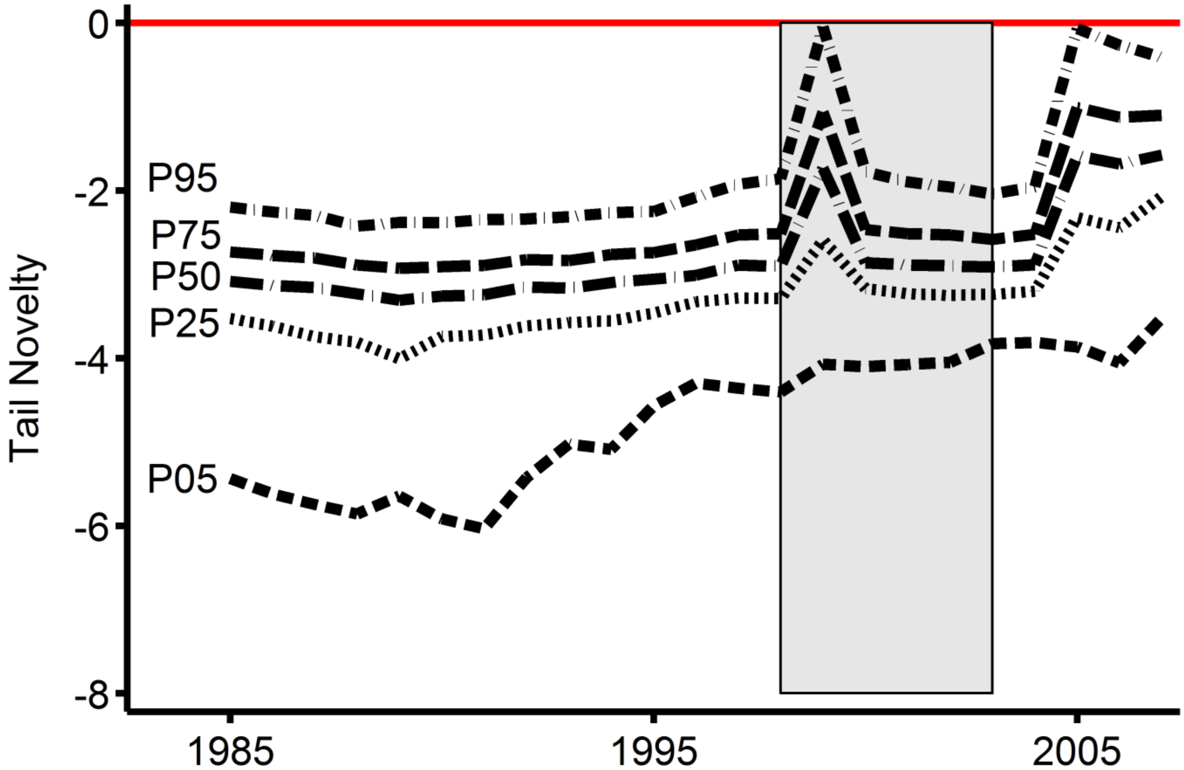


Figure 2.6. Trends in the distribution of median novelty, 1985-2008.



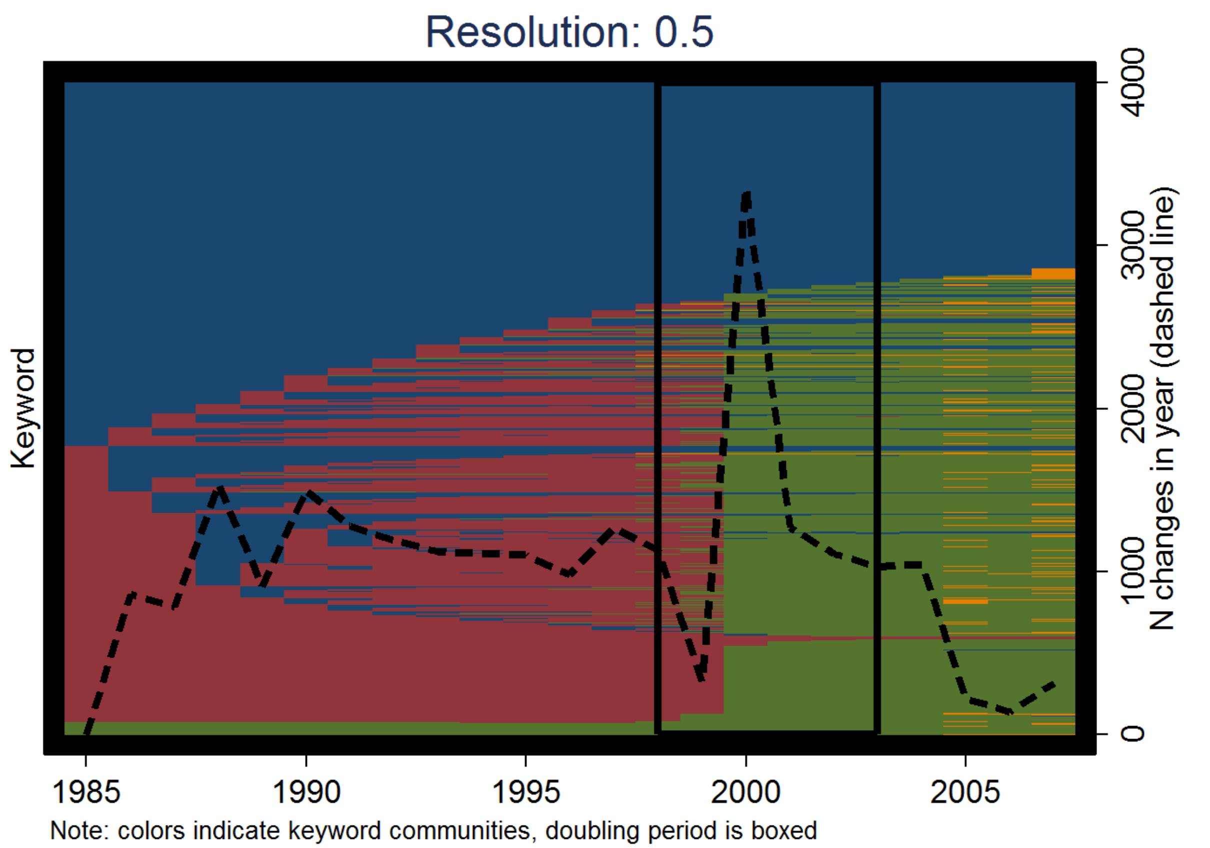
Note: More novel combinations have higher scores. Median novelty reflects the application level median of keyword combinations.

Figure 2.7. Trends in the distribution of tail novelty, 1985-2008.



Note: More novel combinations have higher scores. Tail novelty reflects the application level top decile of keyword combinations.

Figure 2.8. Sequence plot of keyword communities using longitudinal community detection.



Note: The resolution and coupling parameters are both set at 0.5 in this analysis, but sensitivity testing of other values has not shown substantial differences.

Table 2.1. Most common keywords in the data set.

Keyword	Times used
human subject	100,750
clinical research	64,325
laboratory mouse	57,154
tissue /cell culture	52,460
gene expression	43,922
human tissue	32,229
human therapy evaluation	31,864
laboratory rat	31,013
behavioral /social science research tag	25,786
protein structure function	25,393
molecular cloning	22,886
polymerase chain reaction	21,699
genetically modified animals	21,146
biomedical facility	20,383
nucleic acid sequence	20,135
biological signal transduction	19,283
disease /disorder model	19,068
longitudinal human study	18,108
hormone regulation /control mechanism	16,266
immunocytochemistry	16,210

Notes: Keywords are assigned to grant applications as "project terms" by NIH using a thesaurus system; see http://www.nlm.nih.gov/research/umls/sourcereleasedocs/current/CSP/ for more details.

Table 2.2. Example of keyword combinations from a specific application.

Keyword 1	Keyword 2	Times used (1)	Times used (2)	Obs.	Exp.	EOR	ln(EOR)
dna replication;	dna replication;	170	170	170	0.15	0.00	-7.03
neoplasm /cancer genetics;	neoplasm /cancer genetics;	388	388	388	0.79	0.00	-6.20
genetic regulation;	genetic regulation;	480	480	480	1.20	0.00	-5.99
biomedical facility;	biomedical facility;	572	572	572	1.71	0.00	-5.81
transcription factor;	transcription factor;	717	717	717	2.69	0.00	-5.59
genetic regulation;	transcription factor;	480	717	171	1.80	0.01	-4.56
neoplasm /cancer genetics;	transcription factor;	388	717	55	1.45	0.03	-3.63
dna replication;	transcription factor;	170	717	24	0.64	0.03	-3.63
genetic regulation;	neoplasm /cancer genetics;	480	388	30	0.97	0.03	-3.43
dna replication;	genetic regulation;	170	480	11	0.43	0.04	-3.25
dna replication;	neoplasm /cancer genetics;	170	388	8	0.34	0.04	-3.14
biomedical facility;	neoplasm /cancer genetics;	572	388	9	1.16	0.13	-2.05
biomedical facility;	dna replication;	572	170	2	0.51	0.25	-1.37
biomedical facility;	genetic regulation;	572	480	1	1.43	1.43	0.36
biomedical facility;	transcription factor;	572	717	1	2.14	2.14	0.76

Table 2.3. The 20 most commonly used keywords in the emergent orange community which appears after the doubling.

Keywords
visible light;
virus rna;
hypertrophy;
isocitrate dehydrogenase;
phorbols;
immobilization of body part;
thermoreception;
deoxyribopolynucleotide;
jejunectomy /duodenectomy
neoplasm /cancer epidemiology;
aids related neoplasm /cancer;
clinical depression;
androgen analog;
microinjections;
erythema multiforme;
platelet activating factor;
beta hydroxybutyrate;
mammography;
clinical biomedical equipment;
heat injury;

CHAPTER 3: INTERDISCIPLINARITY AND THE NOVELTY OF DISSERTATIONS

Introduction

A growing consensus in academic circles and among federal research funding agencies holds that interdisciplinarity is preferable to disciplinarity (Jacobs, 2014:14-26). More than 70% of faculty across the academy agree with this idea (Gross and Simmons, 2007), and the level of funding for interdisciplinary training and research has grown enormously since the 1980s (Brint et al., 2009). Indeed, it is hard to overstate contemporary enthusiasm for interdisciplinary trends: the convergence of natural, physical, and engineering sciences is being called a "third revolution" in the biomedical sciences (Sharp et al., 2011; Sharp and Langer, 2011:527), while computational and digital approaches to data collection are hypothesized to enable advances in the social sciences and humanities "just as the invention of the telescope revolutionized the study of the heavens" (Lazer et al., 2009; Watts, 2012:266). Shifts toward interdisciplinarity are also celebrated as enabling universities' attempts to "optimize their economic relevance" and become "founts of innovation for a growing economy" (Geiger and Sa, 2008:1). In contemporary reports on interdisciplinarity, the expectation is that these tendencies will continue and become a hallmark of 21st century academic institutions.

According to its proponents, interdisciplinary research creates new knowledge by synthesizing the methods, theories, and data from multiple fields in a way that allows researchers to address pressing scientific issues that otherwise cannot be tackled by a single field alone. Interdisciplinary research also offers the potential for the development of entirely new ideas, as fields borrow from each other and ideas are generated through recombinant innovation (Weitzman, 1998, 1996). Enthusiasm for interdisciplinary research is also driven by antagonism toward its opposite. In this case, however, what stands in contrast to interdisciplinary research is not disciplinary research, per se, but rather disciplinarity as an organizing principle of academia. The symptoms of excessive disciplinarity are thought to include the erection of “major barriers to interdisciplinary research” (Jacobs and Frickel, 2009:48), which is most conveniently articulated in the concept of disciplinary “silos” that fail to communicate outside of their walls (Jacobs, 2014:18).

Prior researchers have tended to examine interdisciplinarity in one of three ways. Several scholars have operationalized interdisciplinary research on the basis of bibliometric data that shows citations to journals in different fields (e.g., Porter and Rafols, 2009). Others have defined interdisciplinary research as work co-authored by faculty members in different departments (e.g., van Rijnsoever and Hessels, 2011). The third definition of interdisciplinarity is institutional, focusing on the documented increase in the number of individuals receiving degrees in what are thought to be interdisciplinary fields (Brint et al., 2009; Jacobs, 2014). Few studies have attempted to integrate across these definitions or considered their relationships with one another. To better understand the relationship between research that bridges fields, the disciplinary organization of university systems, and the interdisciplinary training of future faculty members, I turn to a uniquely promising and neglected area: Ph.D. dissertations and the committees of faculty members that advise them.

Ph.D. dissertations are interesting because they are situated at the nexus of research and professionalization in terms of education, which reflects the training of future scholars and encapsulates the integrated research-education mission of contemporary research universities.

Dissertation committees filter and channel the consequences of larger, disciplinary structures in academia for the types of scholarly work undertaken. To borrow Jacobs' (2014) language, dissertation committees represent one way in which fields talk to themselves, but they also provide an understudied opportunity for fields to speak to each other in university organizations that are largely disciplinary in orientation[2]. The question is: to what extent do they do this? A Ph.D. committee is composed of a group of faculty advising a dissertation, but committee members are linked into broader networks by those who serve on multiple committees. Indeed, the network created by dissertation committee co-membership will, almost by definition, resemble departments as students select department members that they know from prior interactions for their committees. Such network structures may also reveal natural divisions within departments that dissect administrative units; for instance, we may expect Ph.D. committee networks in a geography department to delineate the physical from the human geographers. At the same time, committee ties also have the potential to link across departments and even broader areas of study within universities. It is likely that the boundaries between some fields are more easily crossed than the boundaries between others (Crane, 2010). The prevalence and nature of these crossings is not known, however, either overall or for specific pairings of fields.

Dissertations are more than the committees which advise them, of course. They are also vehicles for scholarly output, holding the questions, methods, and results of research activity, which, for many, is the first major research project of their scholarly careers. Looking across dissertations, we would expect a disciplinary segregation of ideas that reflects the patterns of

[2] For students, disciplines grant degrees, while, for faculty, they offer "homes" in the sense of academic appointments. Interdisciplinary research centers and institutes occasionally serve the latter function, but only very rarely do they serve the former.

committee co-membership networks, as what is discussed and even how it is discussed varies substantially from field to field. But, just as dissertation committees may have members from different fields, dissertations themselves may also integrate ideas in novel ways, bringing concepts or methods from across the research spectrum to bear on particular problems. In this paper, I focus on the relationship between these two processes: disciplinary and interdisciplinary communication at the level of the dissertation committee and the nature of research activity embodied in a dissertation. I hypothesize that there will be a relationship between the novelty of a dissertation and the interdisciplinarity of its committee membership. Further, I ask whether this relationship varies across-areas of study.

Academic fields exist in two interconnected ways; one is cultural, the other structural (Abbott, 2001). The cultural dimension concerns what is being researched, the processes of disciplinary "settlement… the link between a discipline and what it knows" (Abbott, 2001:136), while the structural dimension concerns who is doing this research and their relations to one another. Most studies focus on either the cultural or the structural dimension of interdisciplinarity, but looking at dissertations allows me to examine their interplay. I draw heavily on prior literature about scientific research, interdisciplinarity, and collaboration (e.g., Abbott, 2001; Brint et al., 2009; Foster et al., 2013; Jacobs, 2014; Jacobs and Frickel, 2009; Leahey and Moody, 2014; Moody, 2004; Uzzi et al., 2013; Wuchty et al., 2007). I argue that a focus on dissertations adds to this literature because prior work on this topic has tended to focus on theoretical treatments or else on published papers that are indexed in digital repositories. Doing so neglects attempts at the production of knowledge that do not end up being published as well as scholars who leave the academy, and also selects against fields where scholars do not receive grants, publish indexed articles, or otherwise generate readily available data, such as in the humanities and some social sciences. Such data limitations are not present in the production of dissertations. Indeed, a dissertation is perhaps the defining feature of a Ph.D. degree that is shared across all fields, from art history to chemistry, and all institutions.

Work on research teams has shown that they tend to be better able to integrate novel ideas than single individuals (Uzzi et al., 2013), and that the integration of novel ideas leads to substantially higher scientific impact in terms of citations received. Dissertations and their committee compositions are a particularly interesting venue in which to examine the novel integration of ideas because they are somewhere between a team project and an individual one. Though the work is conducted by an individual, committee members may have substantial input, sometimes enough to qualify them for co-authorship, conditional on disciplinary norms.

To address these issues, I examine dissertations, the makeup of dissertation committees, and the novelty of the ideas examined in each dissertation filed during multiple years at 38 of the largest Ph.D. granting institutions in the United States. These data offer a view of the connectivity of scientific research and university integration, showing both structural as well as cultural features of academic research, but from a different angle than can be seen with citation analyses, co-authorship patterns, or topic models of published papers.

Background

There is considerable confusion over terminology in the literature on interdisciplinary research. To fix terms, in this paper I use the adjectives “interdisciplinary” and “disciplinary” and the nouns “interdisciplinarity” and “disciplinarity” as generic descriptors of a field’s orientation, whether the work conducted in it crosses traditional boundaries (interdisciplinary) or not (disciplinary). I use the nouns field, discipline, and area carefully. I use “field” as a term that includes both traditional disciplines (like sociology or biology) and interdisciplines (like women’s studies or bioethics); that is, I view disciplines as a subset within the broader set of fields. To refer to groups of fields that tend to be similar to each other (e.g., the social sciences) – both in terms of collaboration between faculty and in terms of topics and methods of study – I use the terms “area of study” or “area”. These issues are represented graphically in Appendix Figure 3.A1. There is also a long tradition of terminological debate about the definition of interdisciplinarity. Some distinguish transdisciplinary, multidisciplinary, and interdisciplinary research, depending on the level of synthesis pursued (Jacobs, 2014:78), while others “use interdisciplinary and interdisciplinarity as general terms describing interrelationships between academic disciplines” (Jacobs and Frickel, 2009:45). I do not focus on such distinctions in this chapter.

A broad working definition of interdisciplinarity is offered by the National Academy of Sciences (2004:26), who define interdisciplinary research as “a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories” – i.e., content – “from two or more disciplines or 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.” Teams and integration are key elements in this definition, highlighting how the same two features that Abbott (2001) argues define disciplines – the structure of how they conduct research and the content of that research – are also necessary components in the conduct of interdisciplinary work. In other words, interdisciplinarity is not only characterized by structural and institutional properties, who is doing research and the administrative units of universities such as departments and programs, but, in addition, a core feature is the content of research. This is a mirror reflection of Abbott's view of the social and cultural structures of disciplinary settlements, but it is used to define interdisciplinarity rather than disciplinarity.

To understand interdisciplinarity, it is important to understand the origin of academic disciplines and fields. Academic disciplines have existed since the late middle ages, but the partitioning of scientific knowledge into specific, disciplinary domains was not pervasive until the 19th century (Klein, 1990:20-21) and did not become a defining feature of research universities until the mid-20th century (Jacobs, 2014:1). In the last forty years, however, the number of degree granting institutions offering programs in interdisciplinary fields has grown substantially (Brint et al., 2009:171), and several of these interdisciplinary fields – e.g., women's studies, biochemistry – have developed the hallmarks of disciplines themselves by gaining institutional representation in a large number of universities with substantial undergraduate curricular offerings and a partitioned body of scholarship (Krishnan, 2009). At present, most fields – even the applied and interdisciplinary fields like nursing, education, and business – tend to employ clear majorities of faculty with doctoral degrees in the same field (Jacobs and Frickel, 2009:59). They have created their own internal labor markets. Such tendencies toward internal labor markets are a key aspect of the professionalization of a field as it consolidates into a discipline; the institutionalist perspective even defines disciplines by the existence of such an internal labor market (Abbott, 2001; Jacobs, 2014). Historically, disciplines too have consolidated, as when botany and zoology became biology. The argument in favor of "convergence science" suggests that similar processes are still occurring (Sharp et al., 2011; Sharp and Langer, 2011), though their end results remain unknown.

Inquiry into the nature of disciplines is older than some disciplines. Ben-David and Collins (1966:460) focus on the emergence and persistence of new fields that exhibit "'idea hybridization', the combination of ideas taken from different fields into a new intellectual synthesis", which is also a central aim espoused by those pushing for increased interdisciplinarity in academia. Ben-David and Collins account for these developments by looking at professionalization. They make a structural argument, asserting that new systems of thought do not emerge from ideas alone, rather they arise because of the people who attach themselves to those ideas: "ideas become the end-products of scientific roles, they can be likened to genes which are transmitted from generation to generation through a reliable natural process" (Ben-David and Collins, 1966:459). Based on an empirical analysis of the founding of the discipline of psychology, they situate the attachment of students to professors through the process of discipleship (e.g., Ph.D. committees) as the central locus of such professionalization, albeit one which is modified by the broader network conditions which permit the integration of researchers from multiple fields. This argument provides a clear motivation for investigating the relationship between dissertation committees and the ideas examined in a dissertation, the relationship between the structure of research conduct and the content of that research.

Jacobs and Frickel (2009) review other historical perspectives on disciplinarity and interdisciplinarity. First, they note Abbott's (2001) focus on the professionalization of disciplines: because departments structure the national labor market for Ph.D. job seekers and the hiring processes of universities, a "dual institutionalization", disciplines endure; Abbott argues that absent major shifts in the labor market, they will continue to do so. This argument shares many features with that put forth by Ben-David and Collins. Undergraduate enrollment in disciplinary majors enhances these tendencies as fields compete with each other for students. A second perspective comes from the neo-institutionalist tradition in organization theory (DiMaggio and Powell, 1983), which posits that processes of institutional isomorphism lead universities to copy one another in terms of their disciplinary organization (Sá, 2008). Many contemporary interdisciplinary fields were created in response to social movements (e.g., women's studies, African-American studies, environmental studies), national security interests (most area studies), and changes in technology (computer science, neuroscience) (Jacobs and Frickel, 2009; Rojas, 2007). Others have seen their fortunes fall and rise because of competition for resources other than student enrollments: for example, federal funding priorities in the case of physics and public health. Finally, Jacobs (2014) analyzes citation patterns to note that the research conducted in many fields is connected through a broad web of connections; while sociologists may not cite many neuroscientists, they rather frequently cite psychologists who cite neuroscientists. He argues that this speaking across fields, directly and indirectly, is an ignored aspect of interdisciplinarity and the organization of universities in general and undermines the notion that disciplinary fields themselves are problematic research silos as sometimes portrayed, though there is variability from field to field in these tendencies.

A focus on dissertations and committees aligns well with institutional perspectives on disciplines, Abbott's structural domain, which references their professionalization in terms of semi-closed labor markets and specialized training in the form of graduate education (Abbott, 2001; Jacobs, 2014; Turner, 2000). Of course, it is entirely possible to have interdisciplinary committees and disciplinary degrees; fields may even be better poised to survive when they allow for this kind of interaction between faculty. Indeed, the approach I take to conceptualizing and measuring interdisciplinarity requires organization of the university along disciplinary lines, as Ph.D. committees are typically chaired by a faculty member in the candidate's department with the other faculty members frequently drawn from the same department. While an institutional definition of disciplines holds that “a discipline is defined as a broadly accepted field of study that is institutionalized as a degree-granting department in a large number of colleges and universities” (Jacobs, 2014:27), and thus explicitly emphasizes the macro-level scale, a focus on Ph.D. committee networks in multiple universities emphasizes the structural diversity that exists across fields, as well as the micro-level intersection of disciplinary activities and professional replacement.

My goal is to relate the organization of dissertation committees to ideas in dissertations, Abbott’s cultural domain. We might expect dissertations advised by more diverse interdisciplinary committees to be more novel than those which are advised by a unidisciplinary committee for a variety of reasons. The first reason is because fields borrow ideas. In sociology, many of the borrowed ideas are methodological – a well-known example is Blalock’s importation of multivariate techniques from economics and statistics to sociology (Blalock, 1985, 1965, 1963, 1962, 1961) – but others are theoretical, such as the classic theories of migration flows that built from principles in fluid dynamics and convection (Lee, 1966). Alternatively, there may be a mechanism of contestation and conquest, where fields collide over specific research questions, theories, or methodologies and fight to reorient the debate toward their particular perspective (Abbott, 2001). As disciplinary expansion occurs, new ideas have the potential to break the settled lines of disciplinary agendas and allow the remapping of old debates and the emergence of new forms of scientific consensus (Lakatos, 1980). Postmodernism arguably achieved this in the humanities, drawing even some social sciences like cultural anthropology and a substantial portion of human geography under its tent. Rational choice theory is likely another example. However, these processes are held in check by the structural forces discussed above, producing a pattern of "fractal remapping" (Abbott, 2001).

Thinking about university-wide networks of Ph.D. committee members highlights a key theory in the literature on social networks. The structural theory of networks holds that behaviors are not only affected by local interactions – e.g., having an interdisciplinary committee – but that they are also affected by position in the broader network of relationships, in this case fields and areas of study. This theory most clearly applies with respect to certain diseases, like those which are sexually transmitted, where, for instance, one's risk of contracting the disease does not solely depend on one's number of partners but also how many partners those partners had and whether the network as a whole is connected (Bearman et al., 2004). Without a large, cohesive core of members linked to each other through contact, an epidemic cannot take off. With respect to ideas, however, it is an open question as to how much such structure will matter. Recent work in the social network literature challenges the universality of the strength of weak ties hypothesis (Granovetter, 1973) and suggests that ideas may not always spread across "long", "low bandwidth" ties that link diverse portions of the network (Aral and Alstyne, 2011; Centola and Macy, 2007) but rather require the great density of structurally redundant ties that would be seen within a discipline or field, or else within larger groupings of fields into areas of study that share common orientations. These alternative perspectives have not been assessed with respect to their influence on the generation of new ideas, however, and have not been related to issues of interdisciplinarity.

This review of the literature underscores the importance of asking about contemporary Ph.D. dissertations, the committees that supervise them, the diversity that may exist between fields in the organization of those committees, and the potential consequences of such organization for the advancement of knowledge. It also raises the question of variation between areas of study. It may be that some areas of study are more receptive to interdisciplinary impulses than others, or that particular combinations of areas, as senders and receivers of information, are more frequent and successful. The first questions to be addressed are descriptive. How frequently are Ph.D. dissertations advised by interdisciplinary committees, and is this tendency more prevalent in some areas of study than others? I expect that the amount of interdisciplinarity will vary by area, because some areas of study have more rigid sets of research questions and approaches than others: fields in the social sciences and humanities, for instance, overlap in the topics they address so it may be simpler for dissertations defended in those fields to have cross-disciplinary committee members than fields in the natural and physical sciences. Second, there is the question of interdisciplinary distance. I consider differences in the prevalence and impact of interdisciplinarity within and between areas of study. It seems likely that interdisciplinary research is more common within areas of study (e.g., the social sciences, the humanities) than between them, but how much more common? Does this vary across-areas of study? I expect to see more interdisciplinarity within than between areas of study both because of greater potential overlap in concepts, methods, and data and also because of the way that departments are organized into divisions within university structures (e.g., College of Liberal Arts, School of Engineering). Cross-area collaboration that combines ideas across broad areas of research activity (e.g., between the humanities and the natural sciences) is likely to be rarer, but also more impactful because of the greater potential returns to bridging large gaps in the idea space (Olsson, 2000; Weitzman, 1998, 1996). This pattern has been shown for sub-fields within the discipline of sociology (Leahey and Moody, 2014), but not for larger sets of aggregation.

After documenting variability in the structures of dissertation committees, I turn to the difference this makes in terms of the ideas used in a dissertation. I focus on novelty, which I operationalize as the integration of ideas from multiple fields within a single dissertation. I measure novelty as unexpected combinations of words, which, I later demonstrate, map closely onto notions of fields and areas of study in an idea space of research content. Integrating ideas from different fields is an important outcome of the research process and a defining hallmark of the cultural side of interdisciplinarity. I expect that dissertations which combine ideas in more novel ways will have more interdisciplinary committees, but remain agnostic about whether students choose committee members from other fields owing to the novelty of the dissertation or whether the dissertation becomes more novel because of the presence of committee members from other fields. I also ask whether the novelty of a dissertation varies according to the area of study, both at the level of where committee members come from and the level of which area of study the dissertation is conducted in. Looking at variability here will shed light on the intersection between structural and cultural forces in the generation of new ideas. I expect that some fields may be more accepting of novel work than others. Because fields are organized into areas of study through collaboration and common research agendas and methodologies, this logic should extend to these larger units of aggregation. The remainder of this paper tests these ideas.

Data and Methods

Data

I draw on data from the abstracts of 63,970 dissertations at 38 of the largest Ph.D. granting institutions indexed by ProQuest[3]. Universities were selected for this analysis from a larger list of those appearing in the NSF's list of the top 50 doctorate-granting institutions by number of doctoral recipients in the years 2009-2012 (National Science Foundation, 2014a). There were 54 such programs because there was turnover in which schools made the top 50 cutoff from year to year. The 38 I retain here were those which had at least one year of data with more than 85% of records having more than three committee members named and fewer than 15% of records having a missing department code[4]. I adopted these criteria after manually checking a random sample of 100 records, which revealed that records listing fewer than three committee members were rarely accurate while all of the records which listed three or more committee members were accurate. Some of the schools have only one valid year of data, while others had valid records over the entire observation period from 2007-2013.

The 38 schools I examine in this paper are research powerhouses. In 2013, the most recent year for which data are available, schools in this sample awarded approximately 37% of *all* doctorates granted in the United States, including non-Ph.D. doctorates (National Science Foundation, 2014a), and an equivalent share of *all* research and development expenditures at

[3] Subsequent analyses rely on slightly fewer dissertations as I dropped ones which had missing departmental information of too few words in the abstracts, leaving approximately 63,000 in all cases.

[4] I also dropped four school-years of information that did not meet these thresholds because the number of Ph.D.s listed for the University of Texas in 2012, the University of Michigan in 2013, the Georgia Institute of Technology in 2013, and Stanford University in 2013 in ProQuest diverged by several hundred from the National Science Foundation's Survey of Earned Doctorates estimates for those school-years. These outliers were detected by examining a scatterplot of the two series presented in Table 3.1.

higher education institutions (National Science Foundation, 2014b). Table 3.1 cross tabulates the number of Ph.D. dissertations found in each school and year combination in the data set after dropping school-years which did not contain enough information. It also shows the number of doctorate degrees reported as conferred in that school year in the NSF Survey of Earned Doctorates. The two series are correlated at 0.86, which is quite high. As can be seen, the match between these values is imperfect, but often close. The imperfect overlap between the series can be explained by the different sampling frames – the SED data contain all doctorates not just Ph.D.s while the dissertation data is limited to Ph.D.s – and variation on when dissertations are filed to ProQuest compared to when students complete the NSF survey (some dissertations are defended over the summer, leaving open the chance that these activities are completed in different academic years).

The ProQuest data contain information on the department or degree program in which the Ph.D. was awarded (i.e., the student's department), rather than for faculty members themselves. I code these departments and degree programs into harmonized fields on the basis of a three tiered taxonomy (Berkeley Electronic Press, 2010). From the departmental data listed on the dissertation, I assign each dissertation and all faculty members into one of 141 fields (e.g., Chemistry, Economics, Ecology and Evolutionary Biology) each of which is nested in one of 11 broad scientific areas of study (e.g., Social and Behavioral Sciences, Engineering, Life Sciences). The Berkeley Electronic Press taxonomy provides me with a consistent definition across fields that allows me to match many different degree programs to fields of study and areas at varying levels of specificity.

The dissertations I draw on also contain data on the faculty members which advise them. In total, I found 67,742 unique faculty members at these schools. The names of committee members were used to uniquely identify faculty. First, punctuation was removed, all middle names were turned into initials, and slight name discrepancies between faculty members at the same university were harmonized by merging names if they had a Levenshtein string edit distance of one or fewer (Reif, 2012). It is possible that an unknown but likely small number of faculty members appear in multiple schools, however, if they sat on committees at other schools. Most faculty sit on a small number of committees in these data: the procedures I used suggest that 28,974 (43%) faculty members served on only one dissertation committee at their university, an additional 10,015 (15%) served on two, and 90% of them served on 10 or fewer, but one individual served on a whopping 133 committees in six years of data at Iowa State University[5].

Finally, I assign faculty members to fields and, by implication, areas of studies in the following way. First, if the faculty member is a chair in only one field, then I assign them to be in that field. Otherwise, if they are never seen as a chair or else are a chair in multiple fields, I assign them to the field that they most commonly appear in, breaking 1,593 ties at random. In total, these procedures lead to a conservative set of tests for levels of interdisciplinarity, because false negative rather than false positive name matches are likely to be common when considering only 1 letter differences in names. With low rates of faculty matching across dissertations and the procedure I used to assign fields to faculty, each faculty member is more likely to be assigned to the field of the dissertation chair, decreasing levels of interdisciplinarity compared to data without false negatives.

[5] I investigated the cases who served on inordinately large numbers of committees (75+) by hand. They were all valid cases and do not owe to name disambiguation problems. Unsurprisingly, the individual who served on 133 committees won an outstanding academic advisor award.

Interdisciplinary Extent and Variability

The first set of questions I ask in this paper pertains to the amount of interdisciplinarity that exists in dissertation committee memberships and the degree to which this varies across fields, areas of studies, and universities. To look at this, I begin by examining the proportion of dissertations that have zero, one, two, or three or more members from fields different than the dissertation's chair, which I consider to index the field of the dissertation. Table 3.2 presents results showing these proportions overall and broken out by major area of study. One of the table's most striking results is found in the total row at the bottom: 56% of dissertations in this sample have one or more interdisciplinary committee members; indeed, 19% have two or more. Given the literature's focus on "silos" and excessive disciplinarity in research training, this level of cross-field mentorship is notable. Table 3.2 also reveals considerable variation across areas of study in the composition of committee membership. The Social and Behavioral Sciences fall at the high end of disciplinarity, with 54% of committees having zero members from other fields. Other areas with similarly high levels of disciplinarity include Arts and Humanities (52%), Business (51%), Education (49%), Medicine and Health Sciences (49%), and Physical Sciences and Mathematics (47%). On the other end of the spectrum, areas with low disciplinarity include Law (23%), Architecture (29%), Engineering (29%), and the Life Sciences (31%). The latter two are worth noting because they each contain a large number of dissertations. Law and Architecture are some of the smallest fields in the data set, with only 35 and 207 Ph.D.s respectively, which may explain their high levels of committee members from outside the field.

The next issue I consider deals with interdisciplinary distance when a committee draws members from another field. I ask how often committees draw members from fields that cross areas compared to fields within the same general area. For example, how much more common is it for a Sociology Ph.D. (in the Social and Behavioral Sciences area) to have a Political Scientist (also in the Social and Behavioral Sciences area) on his dissertation committee than a Mathematician (who is in the Physical Sciences and Mathematics area)? In addition, I explore whether these tendencies vary by area. To do this, I look at dissertation level average numbers of members, and decompose this into a) same-field members ("same-field"), b) members from different fields that are within the same area ("same-area"), and c) members from different fields that are in different areas ("cross-area").

Table 3.3 presents these results. On average, across the entire data set, Ph.D. dissertations have 4.1 committee members. This varies somewhat by area of study, with the smallest average numbers of committee members observed in Architecture (3.7), Law (3.8), and Business (3.9) and the largest averages seen in the Life Sciences (4.4), Medicine and Health Science (4.3), and Engineering (4.2). Most members are from the same field. The average dissertation in the data set has 3.3 same-field members. Interdisciplinary committee members from different fields are distributed in an interesting way, however, with dissertation committees having, on average, 0.4 members from different fields in the same area (e.g., a Political Scientist on a Sociology committee) and 0.5 members crossing areas (e.g., a Mathematician on a Sociology committee). It is quite surprising that cross-area interdisciplinarity is more prevalent than within-area interdisciplinarity. There is also substantial heterogeneity in the same- vs. cross-area breakdown of interdisciplinary members by area of study. Some areas (Arts and Humanities, Education, and Engineering) have almost even levels of same- and cross-area committee members, while others are more skewed. Most areas, the exceptions being Arts and Humanities and Life Sciences, have more cross-area interdisciplinary members per dissertation than same-area interdisciplinary members.

While the previous analyses looked at which areas of study tend to have greater levels of interdisciplinarity, they did not consider which areas contributed those interdisciplinary members. That is, how are different areas of study paired in terms of flows of committee members? In Table 3.4, I consider this issue by looking at the average number of interdisciplinary members coming from each area of study (columns), and breaking this out by the area of study of the dissertation (rows). The diagonal cells indicate the number of interdisciplinary members from a different field in the same general area (these values are also shown in the “same-area” column in Table 3.3). The total row is instructive. It shows, for instance, that on average, dissertation committees have 0 interdisciplinary members from Architecture and Law, which makes sense given the small size of these areas. The average dissertation has 0.18 interdisciplinary committee members from the Life Sciences, 0.16 each from Engineering and Physical Sciences and Mathematics, and 0.13 members from the Social and Behavioral Sciences. The average dissertation has fewer interdisciplinary members from the Arts and Humanities (0.09), Business (0.02), Education (0.04), and Medicine and Health Sciences (0.04). Clearly, some of these tendencies reflect the size of each field and its ability to contribute interdisciplinary members.

More interesting than the global average, however, is how areas differ in terms of the areas from which they draw interdisciplinary members. Of course, as would be expected on the basis of Table 3.3, the diagonal cells of the table – those which measure interdisciplinary members from the same area – tend to contain the largest values. Considering the cross-area committee members, the principal findings are as follows: members from the Social and Behavioral Sciences, followed by Life Sciences, most frequently appear as cross-area committee members. Dissertations in Architecture, Arts and Humanities, Business, Education, Law, and

Medicine and Health Sciences all have more than 0.1 committee members from the Social and Behavioral Sciences, on average. The average dissertation in Architecture, Medicine and Health Sciences, and Physical Sciences and Mathematics has more than 0.1 committee members from the Life Sciences. Generally, there is a break between the so-called “hard” and “soft” sciences, with higher levels of interdisciplinary members crossing areas within these groups than between them. Social and Behavioral Sciences is the exception to this, donating committee members to many other areas, which presents an interesting contrast to the earlier results because Social and Behavioral Science Ph.D.s were some of the least likely to have interdisciplinary committee members themselves, drawn either within their area or from other areas (see Tables 3.2 and 3.3).

So far, I have considered interdisciplinarity at the level of dissertation committees. Descriptively, I have shown that a surprising number of Ph.D. committees contain interdisciplinary members and that much of this interdisciplinary advising occurs across rather than within areas of study. These findings compare favorably with those presented by Jacobs (2014), who argued that even disciplinary fields are not isolated “silos” who do not communicate with each other, but rather are linked together through webs of scholarship. Here, I show that these webs extend to the training of the next generation of researchers, that interdisciplinarity is thriving in the context of academic reproduction. I also document variability by area of study, both in terms of borrowing (committee members) from other fields and also in terms of loaning. A striking finding here was that the Social and Behavioral Sciences tend to loan committee members to other fields quite frequently, but they also tend to borrow them infrequently. Such a finding may be consistent with other work which highlights the central role of the social sciences in citation networks (Moody, 2004). In the next section, I will consider the association of these patterns with the research conducted in each dissertation.

Effects of structural interdisciplinarity on novelty

The next set of questions I ask pertains to whether the structure of dissertation committees, particularly with respect to interdisciplinarity, is associated with the novelty of the research undertaken in a dissertation. I define the novelty of a dissertation as the extent to which it integrates key ideas that are rarely examined in conjunction; that is, I relate the novelty of a dissertation to the novelty of its combinations of key concepts. This approach is informed by the prior literature on novelty in scientific research. Nearly identical approaches have been used by others to define the novelty of publications on the basis of unexpected combinations of journal citations (Uzzi et al., 2013), assigned disciplinary subfields (Leahey and Moody, 2014), or chemical compounds being analyzed (Foster et al., 2013). The idea of applying these methods to topics is explicitly suggested in Uzzi et al.'s work (2013:469). An intuitively novel dissertation might be one that uses theories and methods from physics and engineering to study the causes of racial segregation in the friendship choices of adolescents, for instance. I operationalize the novelty of a dissertation using high-signal words I extract from the abstracts of each dissertation on the basis of term frequency inverse document frequency. In the supplemental appendix, I present a replication of these analyses on the basis of the listed keywords for each dissertation which shows nearly identical results and suggests that the conclusions reached here are robust to alternative specifications of the key ideas being researched in each dissertation. I expect that the same approach applied to other measures of a dissertation's content, such as topic models, would yield the same results.

To extract the key terms being researched in each dissertation, I first parse the abstracts into separate word tokens. I then remove all characters that were not alpha-numeric, and convert alphabetic characters to lower case. Next, I calculate the term frequency – inverse document frequency scores for each word, an information retrieval metric which measures the signal of a term in terms of its distinctiveness. Terms with high term frequency – inverse document frequency tend to be used often in a small number of dissertations, indicating that the term is important to that dissertation. Finally, for each dissertation, I select the top 20 highest signal terms in each abstract. At this stage, I eliminated 208 dissertations with fewer than 50 terms from the remaining analyses because these may have had too few words for a meaningful data extraction. Focusing on a fixed number of terms like this ensures that the number of term combinations in each dissertation is comparable.

I found 115,905 unique terms via term frequency – inverse document frequency. Table 3.5 shows the number of times words are used in the data set. The majority (54%) of these are used more than six times, while approximately 10% are used only one time. The frequency with which each key term is used in the data set and the number of dissertations in which each keyword is used are shown in Table 3.5. The 40 most commonly used terms are listed, with their number of uses, in Table 3.6. The most commonly used words reflect key concepts such as education, health, or protein.

Because I select 20 key terms from each dissertation, I can create 190 (=[20*20-20]/2) combinations of terms for each dissertation. I use the frequency of term co-occurrences within dissertations to define, across all dissertations, the idea space of contemporary research. By idea space, I mean the clustering of concepts, i.e., how frequently they tend to be used together. Most fields have their own vocabulary and jargon, so we would expect that concepts and the ways researchers talk about them cluster. For instance, demographers often talk about the population at risk and sampling, network scientists talk about degree distributions and connected components, and sociologists of stratification talk about race, class, and gender. We would expect that these concepts would be more closely linked to each other than they would be to ideas like laboratory rats, proteins, etc. At different resolutions we would expect that the clustering of ideas differentiates areas of science (e.g., the human sciences from the physical) but also fields within areas (e.g., sociology from economics).

Figure 3.1 shows an example of idea space measured through keyword co-occurrence (the keywords used in the supplemental appendix to test robustness of the term based method presented here; I constructed a similar figure on the basis of terms, but the density of ties is much larger because each dissertation contributes 190 ties to the data, which impedes visual interpretability). To facilitate visualization, I retain links between keywords only if they co-occur in more than 10 dissertations, and I eliminate keywords that were not in the largest connected component formed by such links. These choices do not induce the patterns seen in the figure: a comparable analysis based on all keywords showed a very similar organization (not shown). I size nodes according to the number of other keywords to which they linked (i.e., by degree). Colors represent the community in which keywords are situated, with communities algorithmically detected by modularity maximization (Louvain method, resolution=1; see Mucha et al., 2010). The graph is laid out by a force directed algorithm (YiFan Hu Proportional) in the Gephi software package (Bastian et al., 2009). On the left there are large clusters of keywords that tend to link to one or two central hubs and to each other, while on the right there is quite a bit of fuzziness with the beige nodes pulled in multiple directions.

Dissertation word co-occurrences reproduce the disciplinary organization of contemporary scientific ideas, which is unsurprising because fields have their own vocabularies. The labels facilitate interpretation of Figure 3.1. Pure and applied sciences are the dark blue nodes on the bottom right of the graph, and they tend to share a considerable cluster of keywords. They each have their own keyword clusters as well. The biological and health and environmental sciences are the light blue nodes at the top right of the graph; they also have shared and distinct keyword vocabularies. The green nodes representing earth sciences at the bottom of the graph are interesting as they tend to not share many keywords with other areas of study, but they are also a small area of study as measured here. On the left side of the graph, the deep red nodes show the social sciences, which have a very cohesive set of terminology. Many other nodes are connected to the social sciences hub node, however. Most of these are in the humanities (e.g., religion and theology, philosophy, communication and the arts) while others concern topics of interest to both humanities and social science scholars (race and gender, which were almost on top of each other before adjustment to prevent overlap). These humanities nodes are scattered throughout the left of the graph and are linked quite closely with the final community that was detected, the pink nodes, representing psychology and education.

Overall, Figure 3.1 shows the idea space of research being conducted in recent dissertations. Importantly, the idea space shown in this figure maps onto a frequently noted division in academic research between purportedly "soft" and "hard" sciences. At finer scales, the differences between areas of study can be seen, such as the divisions between the biological sciences and pure and applied sciences. Figure 3.1 also makes clear that some areas of study tend to be closer to each other than they are to others. For instance, the biological sciences share a substantial amount of vocabulary with the health sciences but less with the social sciences. At even finer scales, we might expect to see divisions that represent fields within areas. In the remainder of this paper, I relate the novelty of a dissertation in terms of its combinations of ideas to its committee composition. Based on Figure 3.1, it would be more novel for a keyword in the social science portion of the graph to co-occur with a keyword in the natural science portion than for a keyword in the social science portion to co-occur with a keyword in the humanities portion (remember, Figure 3.1 only plots links between keywords that co-occur frequently). I do not define novelty conditional on area, but I examine differences between areas in their levels of novelty.

To translate the terms used in a dissertation into a measure of novelty, across all dissertations in the data set, I count the number of times pairs of terms co-occur in a dissertation in any and all fields. I define the novelty of a dissertation as the unexpectedness of its pairwise term combinations using the natural log of their observed/expected ratio. Formally, I calculate the novelty of a combination of two terms as the natural log of the ratio of their expected frequency of appearing in the same dissertation under independence to their observed frequency of appearing in the same dissertation: $oer_{ij} = \ln\left(\frac{k_i k_j / sum(k_{ij})}{k_{ij}}\right)$, where k_i is the frequency with which term i is used across all dissertations, k_j is the frequency with which term j is used across all dissertations, and $k_i k_j$ is the frequency with which dissertations list both terms i and j.

Table 3.7 lists the 20 most novel keyword combinations by this measure as well as their observed/expected ratio, and counts of expected and observed co-occurrences. Many of the most novel combinations include the integration of concepts from the social sciences and humanities with those from formal or natural sciences. For instance, the most novel combination, observed twelve times but expected 2,108, are "'students' and 'cell'", with the former being a word frequently examined in the social and humanistic research traditions and the latter being a word used more often in the life and health sciences. Some of the word combinations may seem strange, such as "teachers" and "t". However, an examination of the abstracts in which these words were used showed that they made sense in context; for instance, in the case of "teachers" and “t”, these papers were referring to the statistical tests known as t-tests, which tend to be used frequently across the corpus but rarely in combination with teachers. Other combinations are less meaningful, however, such as “mothers” and “chapter”. I examined the abstracts in which these were used in combination, and “chapter” in these contexts refers to chapter of the dissertation. It is unlikely that this particular example represents a meaningful combination. Nonetheless, it presents an interesting view onto the ways dissertation writers use language in predictable ways; though many have written about mothers, few of them refer to the chapters of their dissertations in the abstract. Many of the least novel term combinations in the data are names, such as “‘Ernest’ and ‘Hemingway’”, which tend to be rare individually but examined in conjunction frequently.

The logged observed/expected ratio just described is calculated at the level of term combinations. I translate this to the dissertation level with two metrics. First, for each dissertation, I define core novelty by taking the median logged observed/expected ratio across its pairs of keywords. Second, I define the tail novelty of a dissertation as the maximum logged observed/expected ratio of its term combinations. Figure 3.2 shows the cumulative distributions of core and tail novelty across dissertations. Table 3.8 shows two dissertation abstracts. The top abstract from the field of computer sciences deals with new approaches to robotics, and is classified as a novel dissertation on both the core and tail novelty measures (top 1% of both distributions). The bottom abstract from mathematics is classified as not a novel dissertation (bottom 5% on both measures). Uzzi et al. (2013) used a similar approach to define conventional and tail novelty in journal articles, but on the basis of bibliographic combinations rather than combinations of terms (they suggest terms could be used, however). They found that articles which displayed high core and tail novelty had double the background probability of being in the top 5% of the distribution of most cited articles, indicating that novelty may have a substantial effect on the scientific influence of an article. Similar approaches have been used in other work to account for the chance occurrence that given pairs will co-appear at random and are familiar from the χ^2 testing tradition (Leahey and Moody, 2014; Morris, 1991; Morris et al., 2009; Schilling and Green, 2011).

Analytic Models

I analyze the core and tail novelty of dissertations using ordinary least squares regression. In all models, I control for the area of study, year, and university in which a dissertation was conducted to mitigate differences that might exist between universities, over time, or by area of study. Though there are interesting questions to ask about variability in these features, they are beyond the scope of this analysis. Instead, I begin by examining the effects of committee members, then consider interdisciplinary members, then cross-area members, and finally cross-area members from each area of study. Unfolding the analysis in this way helps to clarify the mechanisms which impact dissertation novelty. Because each additional variable added to the model is a subset of the former variables of interest, I can gauge the net contribution of, for instance, adding an interdisciplinary member after accounting for the change that would occur because of adding any type of member. After considering the effects on all dissertations, I explore another set of interactive models which estimate effects of cross-area committee members from each area of study on each area of study.

Results

Table 3.9 presents the results of the relationship between dissertation committee structure and novelty, both at the core and tail of term combinations in each dissertation. Model 1 demonstrates a negative association between the number of members on a dissertation committee and its core novelty. Model 5 shows the same for tail novelty, but the results are not significant even though they are in the same direction. Models 2 and 6 add the number of members who are interdisciplinary, that is, from different fields than the field in which the dissertation was conducted. The number of interdisciplinary members is associated with an increase in novelty, at both the core and tail of keyword combinations. Models 3 and 7 add cross-area members. For core novelty (model 3), when cross-area members are incorporated, the significance of the coefficient for interdisciplinary members disappears and the magnitude drops by approximately 2/3rds. Cross-area members, those from areas of study that differ from the area of study of the dissertation, have a strong positive association with core novelty. The patterns for tail novelty are slightly weaker, but in the same direction.

Models 4 and 8 in Table 3.9 decompose the cross-area member variable by the area of study from which each member came. Cross-area members from three areas of study have consistent results for both core and tail novelty. Arts and Humanities committee members serving on dissertations outside of their own area are associated with a substantial decrease in both core and tail novelty. To put this into context, these coefficients are approximately 10 times the magnitude the omnibus cross-area coefficients presented in models 3 and 7. Second, cross-area committee members from the areas of Education and the Social and Behavioral Sciences have strong positive associations with novelty in the core and tail of a dissertation's keyword combinations. Cross-area members from other areas of study have more mixed results; those from Architecture, Health Sciences and Medicine, and Physical Sciences and Mathematics lack associations that are statistically distinguishable from sampling variability. Those from Business and Engineering have a positive association with core novelty, but no meaningful association with tail novelty. Cross-area members from Law are negatively associated with tail novelty, but not core novelty. Finally, cross-area members from one of the larger areas of study, Life Sciences, have a negative association with core novelty and no association with tail novelty.

Table 3.10 presents results for core novelty stratified by the area of study in which the dissertation was conducted. Each column of the table shows effects for dissertations conducted in one area; the rows examine the same ideas as in Table 3.9. Importantly, the number of interdisciplinary members variable in this table should be interpreted as interdisciplinary members from the same area of study. Dissertations in the areas of Architecture and Arts and Humanities show a negative association between core novelty and the number of interdisciplinary members from their own area. Those in Education, Engineering, Physical Sciences and Mathematics, and Social and Behavioral Sciences all show positive associations between core novelty and the number of interdisciplinary members from their own area. Cross-area members from Architecture are negatively associated with the core novelty of dissertations in Social and Behavioral Sciences. The strong negative impact of cross-area members from Arts and Humanities on core novelty shown in Table 3.8 is only found for dissertations in the areas of Education, Health Sciences and Medicine, and Social and Behavioral Sciences. However, the strong positive impacts on core novelty of cross-area members from Education are repeated across a large range of areas: Arts and Humanities, Engineering, Life Sciences, Health Sciences and Medicine, Physical Sciences and Mathematics, and Social and Behavioral Sciences. The positive effects on core novelty of cross-area committee members from Social and Behavioral Science area also repeated across a number of areas, with the exception of a negative effect on dissertations in Education. Committee members from Business tend to have positive associations across the board, most notably with Architecture, Arts and Humanities, Engineering, and Physical Sciences and Mathematics dissertations.

Cross-area members from other areas have more variable patterns, affecting core novelty in some areas positively and negatively in others. Numbers of cross-area committee members from Engineering, for instance, are positively associated with the core novelty of dissertations in Architecture and Physical Sciences and Mathematics, but negatively associated with the core novelty of dissertations in Health Sciences and Medicine. Cross-area members from the Life Sciences seem to positively affect the core novelty of Arts and Humanities dissertations but negatively affect the core novelty of dissertations in several other areas: Education, Engineering, Health Sciences and Medicine, Physical Sciences and Mathematics, and Social and Behavioral Sciences. Physical Sciences and Mathematics committee members, when they cross areas to Arts and Humanities and Life Sciences, tend to be associated with greater core novelty. However, they are negatively associated with the core novelty of dissertations in Health Sciences and Medicine, and Social and Behavioral Sciences. Finally, the presence of cross-area members from Health Sciences and Medicine is positively associated with the core novelty of dissertations in the Physical Sciences and Mathematics, and Arts and Humanities, but negatively associated with core novelty for dissertations in Education and Engineering.

Table 3.11 shows the same analyses conducted for tail novelty. It contains a remarkable result: only two cells in the cross-area committee member matrix are negative. Specifically, cross-area members from Arts and Humanities and Business are negatively associated with the tail novelty of Social and Behavioral Science dissertations. All of the other statistically significant cross-area member coefficients are positive, indicating a near universality of the beneficial relationship between cross-area committee members and the tail novelty of a dissertation.

Discussion

Does the interdisciplinarity of a dissertation committee relate to the novelty of its research? In this paper, I considered this question and others about the prevalence of interdisciplinarity in the training and mentorship of Ph.D. students by looking at dissertation committee composition and the unexpectedness with which ideas are combined in the dissertation. In contrast to oft-highlighted concerns about the siloed nature of graduate training and the insularity of disciplines seeking to reproduce themselves, I found surprisingly high levels of interdisciplinarity in dissertation committee membership across 38 of the largest research universities. Indeed, more than half of dissertation committees contained at least one member from a different field and the average dissertation had a half a member from an entirely different area of study. The potential flow of knowledge between fields through dissertation committees was not random, however, as there tended to be higher levels of cross-area committee membership within the “hard” and “soft” sciences than between them. The Social and Behavioral Sciences were an exception to this, contributing a substantial number of members across all areas. Looking at academic fields as a web of connections that have greater density within fields than between them, the Social Sciences appear central, a finding that has been demonstrated in other work on citation practices (Moody, 2004).

It is reasonable to wonder whether the high levels of interdisciplinarity in committee membership has an impact. I found that it does, at least in terms of the novelty of idea combinations, but that these effects tend to be limited to the presence of cross-area members rather than interdisciplinary members from the same area. In the aggregate, cross-area members have a strong positive association on both the core and tail novelty of a dissertation. Breaking it down by the field where cross-area members come from, however, reveals that Humanists tend to decrease novelty in other fields while those in Education and Social and Behavioral Sciences tend to increase it. However, when looking more closely at the data by considering the effects of cross-area members on each area, we see a different set of results. Things are complicated for core novelty, meaning that cross-area members from a given area will affect the conventionality of dissertations in different ways depending on the area in which the dissertation was conducted. However, tail novelty, the kind most strongly associated with boosts in citation counts of published papers (Uzzi et al., 2013), does not show this tendency. Indeed, with the exception of dissertations conducted in the Social and Behavioral Sciences which appear to be negatively affected by committee members from the Business and Arts and Humanities areas, the presence of cross-area members is almost never associated with decreased tail novelty and in many cases is beneficial.

Conclusion

This paper investigates a new source of data on interdisciplinarity and speaks to the training of the next generation of scholars. I relate the structural and cultural aspects of academic research – the relations among who is doing the research and what is being researched – showing that those whose dissertation committees contain members from very different fields tend to conduct more novel research.

A strength of this paper is its coverage. While it is not a probability sample, and thus is challenging to generalize, the data contain information on more than one hundred Ph.D. fields from across the academic landscape. These data represent a substantial share of the Ph.D.s graduated in the United States in the 2007-2013 period. Many of the sociological writings on interdisciplinarity have focused on fields in the Social and Behavioral Sciences or else in Arts and Humanities (Abbott, 2001; Jacobs, 2014; Rojas, 2007), to the neglect of what occurs in Engineering, for instance. Other work has focused on fields which produce articles indexed in digital repositories with less focus on the humanistic fields that are poorly covered by such indexes (Uzzi et al., 2013; Wuchty et al., 2007). All fields are well covered in the analyses I present. Dissertations are a unit of academic output produced by all Ph.D.s (by definition), not only those who obtain research jobs and publish peer reviewed literature. Looking at them has the potential to offer a more complete picture of the scientific landscape, at least with respect to the training of the next generation of scholars. An interesting future direction in which this work could be taken would be to follow up the individuals in question, examining their career trajectories and outcomes, and asking who stayed in academic research and who left and whether this is predictable on the basis of their dissertation committees and dissertation novelty.

A limitation of this paper is that I relied on a convenience sample of large schools, constrained to some of the largest research universities that in combination award a large share of all Ph.D.s granted in the United States. Whether these results would generalize to other schools with smaller programs, which have fewer available members in each department, or to other countries with different models of university organization is a direction that future work could pursue. Indeed, the coverage of Ph.D. committee members in the ProQuest data appears to be getting better every year, which may make such analyses more feasible in the future.

Considering the entire landscape of academic research at large universities reveals some general patterns, reaffirming that interdisciplinarity – the more distant the better – appears to relate strongly to novel research production, though I do not claim that this is a causal effect. I did not set out to address causal issues. I cannot separate whether students who are conducting novel research seek out interdisciplinary committees or whether the effect runs in the opposite direction, such that interdisciplinary committee members inject or enhance the novelty of a dissertation. There is the potential to take advantage of the longitudinal nature of these data – committee members appear over multiple years – but a key challenge is that each dissertation appears in the data set only once. Nonetheless, even without causal certainty, the relationship between dissertation committee structure and the novelty of the work conducted is interesting.

Universities differ in their Ph.D. requirements, and there are differences within universities between administrative units (e.g., School of Public Health vs. College of Liberal Arts). Some require that all committees contain an outside member, while others do not, though I did not find evidence that all dissertations within a school have members from multiple fields. Nonetheless, administrative requirements regarding outside members is a potential mechanism universities or agencies which fund dissertation research (e.g., the National Science Foundation) could pursue in an effort to increase the novelty of dissertation research being conducted. However, the results in this paper suggest that administrators would be best off pushing for interdisciplinarity that crosses areas of study, requiring students to select members from substantially different fields, which may be challenging to implement. In addition, the success of such measures may depend on the causality of the results documented in this paper. If students who have a tendency to write novel papers select disciplinarily diverse committees, then such a policy may have little effect. If the relationships run in the opposite direction, however, with committee members from different fields injecting novel perspectives into dissertations, then such policies may lead to more path-breaking research.

Contemporary dissertation committees in the United States are surprisingly interdisciplinary, and those dissertations which are interdisciplinary tend to be more novel than those which are not. This broad relationship gives way to nuances at the level of specific fields. Humanists and life scientists tend to have negative impacts on core novelty – the median level of term combinations in each dissertation – for many fields, but their impact on tail novelty – the most novel combination in each dissertation – is often positive, except that Arts and Humanities scholars appear to negatively impact the tail novelty of Social and Behavioral Science dissertations. By contrast, having an interdisciplinary committee member from the Social and Behavioral Sciences tends to be positive for the core novelty of all areas except Education; having a social scientist also tends to be positive for the tail novelty of several fields, especially those in the natural and physical sciences. In all, this chapter demonstrates a lively and beneficial exchange of ideas between academic fields that occurs during dissertations, ideas which may have broad implications for the future of interdisciplinary research.

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Table 3.1. Dissertations in data set and doctorates as reported in NSF SED. Note: Correlated at 0.861. SED contains other doctorates in addition to Ph.D.s.

	Dissertations (Ph.D.s)						
School	**'07**	**'08**	**'09**	**'10**	**'11**	**'12**	**'13**
Arizona State U.					424	303	442
City U. of New York		336	380	390	379	432	472
Cornell U.							408
Duke U.			306	320	327	342	345
Florida State U.						376	350
Harvard U.						590	502
Indiana U., Bloomington		393	425	403	414	455	405
Iowa State U.		288	307	326	346	379	358
Johns Hopkins U.							350
Michigan State U.					412	483	495
New York U.		385	355	344	373	382	393
Northwestern U.		347	357	339	376	457	427
Ohio State U.						705	
Princeton U.						353	332
Purdue U.	556	610	570	629	511	633	634
State U. of NY, Buffalo			249	285	293	319	233
U. Arizona			448	425	405	419	430
U. California, Berkeley				674	878	654	540
U. California, Davis			270	437	526	590	502
U. California, Irvine				356	371	412	410
U. California, Los Angeles						724	696
U. California, San Diego		393	372	404	474	488	437
U. California, Santa Barbara		308	310	302	319	344	374
U. Chicago				391	376	421	396
U. Colorado, Boulder		260	257	322	321	349	347
U. IL, Champagne-Urbana						521	478
U. IL, Chicago						310	
U. Iowa				339	362	329	264
U. Maryland, College Park			313	525	583	656	566
U. Minnesota, Twin Cities			666	716	398	671	641
U. NC, Chapel Hill	561	400	475	513	356	464	552
U. Pennsylvania						426	453
U. Pittsburgh							435
U. Southern California		432	452	421	356	460	457
U. Texas, Austin			603				
U. Washington, Seattle						491	637
U. Wisconsin, Madison						748	672
Walden U.		182	203	363	375	395	508

Table 3.1 continued.

	NSF SED Doctorates (all)						
School	**'07**	**'08**	**'09**	**'10**	**'11**	**'12**	**'13**
Arizona State U.					408	442	465
City U. of New York		358	361	365	433	427	450
Cornell U.							488
Duke U.			317	329	317	342	370
Florida State U.						395	344
Harvard U.						694	674
Indiana U., Bloomington		398	421	425	406	402	448
Iowa State U.		310	316	300	357	376	349
Johns Hopkins U.							487
Michigan State U.					451	478	504
New York U.		409	383	364	399	396	393
Northwestern U.		353	360	361	369	367	469
Ohio State U.						691	
Princeton U.						351	319
Purdue U.	609	597	646	627	671	645	686
State U. of NY, Buffalo			312	273	295	295	329
U. Arizona			454	425	409	415	409
U. California, Berkeley				865	878	864	911
U. California, Davis			500	464	491	553	567
U. California, Irvine				365	374	409	434
U. California, Los Angeles						687	742
U. California, San Diego		448	417	437	484	513	485
U. California, Santa Barbara		344	346	294	343	338	373
U. Chicago				368	395	401	412
U. Colorado, Boulder		307	291	311	353	343	375
U. IL, Champagne-Urbana						811	756
U. IL, Chicago						321	
U. Iowa				343	359	369	396
U. Maryland, College Park			529	571	548	587	658
U. Minnesota, Twin Cities			682	702	710	721	761
U. NC, Chapel Hill	464	561	440	499	479	472	496
U. Pennsylvania						442	443
U. Pittsburgh							419
U. Southern California		571	645	445	431	448	447
U. Texas, Austin			737				
U. Washington, Seattle						580	645
U. Wisconsin, Madison						793	735
Walden U.		203	199	287	343	387	438

Table 3.2. Proportion of dissertations with 0, 1, 2, and 3+ interdisciplinary committee members, overall and by area of study.

	Pr. with X interdisciplinary members				
Area of study	**0**	**1**	**2**	**3+**	**Total**
Architecture	0.29	0.49	0.17	0.05	207
Arts & Humanities	0.52	0.33	0.10	0.04	8,235
Business	0.51	0.35	0.11	0.03	1,961
Education	0.49	0.35	0.12	0.04	4,199
Engineering	0.29	0.44	0.20	0.07	10,563
Law	0.23	0.51	0.23	0.03	35
Life Sciences	0.31	0.35	0.21	0.13	9,060
Medicine & Health Sciences	0.49	0.32	0.13	0.06	3,495
Physical Sciences & Mathematics	0.47	0.36	0.12	0.05	12,652
Social & Behavioral Sciences	0.54	0.34	0.09	0.03	12,648
Total	0.44	0.36	0.14	0.05	63,055

Table 3.3. Average number of committee members, same field members, and within- vs. between-area members, overall and by area of study.

Area of study	**Members**	**Same field**	**Same-area**	**Cross-area**
Architecture	3.7	2.7	0.1	0.9
Arts & Humanities	3.9	3.2	0.4	0.3
Business	3.8	3.1	0.1	0.6
Education	4.0	3.2	0.3	0.4
Engineering	4.2	3.1	0.5	0.6
Law	3.8	2.8	0.0	1.1
Life Sciences	4.4	3.2	0.7	0.5
Medicine & Health Sciences	4.3	3.5	0.1	0.7
Physical Sciences & Mathematics	4.1	3.4	0.3	0.5
Social & Behavioral Sciences	4.0	3.4	0.2	0.4
Total	4.1	3.3	0.4	0.5

Note: "Same-area" measures number in a different field in the same area, "cross-area" measures different field in a different area.

Table 3.4. Average numbers of interdisciplinary dissertation committee members serving within and between areas, rows represent the receiving area (dissertation area) and columns represent the sending area.

Diss. area	**Mean interdisciplinary/cross-area members from each field**									
	Arc	**A&H**	**Bus**	**Edu**	**Eng**	**Law**	**LS**	**MHS**	**PSM**	**SBS**
Arc	0.09	0.12	0.03	0.03	0.11	0.00	0.21	0.02	0.05	0.32
A&H	0.00	0.44	0.00	0.03	0.01	0.00	0.01	0.00	0.02	0.16
Bus	0.00	0.01	0.11	0.05	0.05	0.00	0.01	0.02	0.08	0.34
Edu	0.00	0.06	0.02	0.30	0.02	0.00	0.03	0.03	0.05	0.20
Eng	0.00	0.00	0.01	0.01	0.50	0.00	0.12	0.03	0.35	0.04
Law	0.00	0.14	0.06	0.00	0.00	0.00	0.00	0.03	0.00	0.83
LS	0.00	0.01	0.00	0.01	0.11	0.00	0.68	0.11	0.19	0.08
MHS	0.00	0.01	0.02	0.04	0.07	0.00	0.26	0.10	0.12	0.17
PSM	0.00	0.01	0.01	0.01	0.24	0.00	0.15	0.03	0.25	0.06
SBS	0.00	0.10	0.04	0.06	0.02	0.00	0.05	0.04	0.06	0.23
Total	0.00	0.09	0.02	0.04	0.16	0.00	0.18	0.04	0.16	0.13

Note: Arc=Architecture; A&H=Arts & Humanities; Bus=Business; Edu=Education; Eng=Engineering; Law=Law; LS=Life Sciences; MHS=Medicine & Health Sciences; PSM=Physical Sciences & Mathematics; SBS=Social & Behavioral Sciences. The rows show each area of study for the dissertation, while the columns show the number of interdisciplinary members from a given area of study. Off-diagonal cells show the number of cross-area members from each area of study, while diagonal cells show the number of interdisciplinary members from the same area of study. Small fields, like law and architecture, do not contribute many interdisciplinary members.

Table 3.5. Summary statistics of key terms found in the data.

Term level:	Times used in data set	Dissertations term used in
Number unique	115,905	115,905
Proportion used 1	0.10	0.00
Proportion used 2	0.17	0.42
Proportion used 3	0.08	0.20
Proportion used 4	0.06	0.12
Proportion used 5	0.05	0.08
Proportion used 6+	0.54	0.18

Table 3.6. The 20 most commonly used key terms in the data set.

Rank	Key	Times Used in
1	students	15,068
2	chapter	12,529
3	cells	12,337
4	social	9,540
5	cell	8,796
6	2	8,741
7	health	7,493
8	school	6,816
9	learning	6,651
10	children	6,618
11	women	6,575
12	teachers	6,271
13	model	5,851
14	protein	5,683
15	data	5,651
16	cancer	5,606
17	political	5,604
18	network	5,390
19	risk	5,316
20	energy	5,267

Figure 3.1. The idea space of contemporary dissertation research as measured through frequent keyword co-occurrence in the same dissertation.

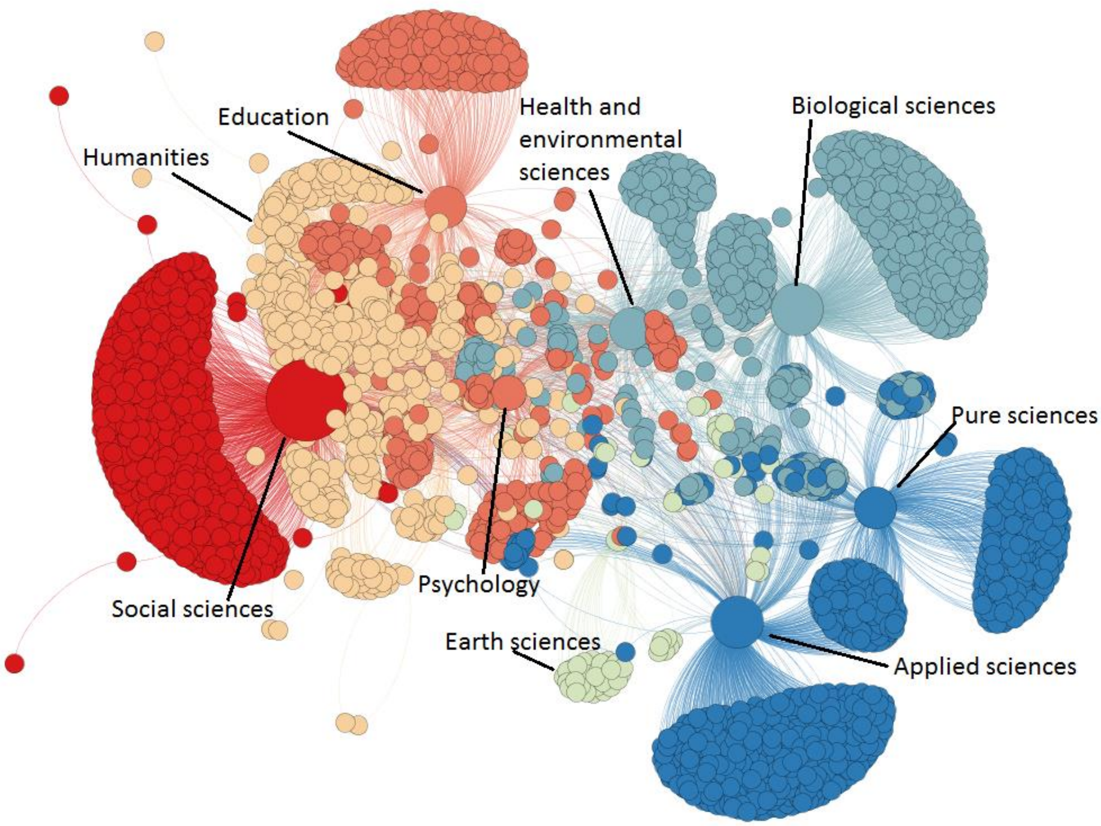

Table 3.7. Most novel combinations of terms in the data set.

Term 1	Term 2	OER	Obs.	Exp.
students	cell	5.17	12	2108
students	firms	4.94	6	842
students	c	4.91	6	812
mothers	chapter	4.79	3	359
protein	online	4.64	2	208
network	children	4.55	6	567
students	light	4.41	4	329
sex	learning	4.35	2	156
students	marine	4.35	2	155
systems	cells	4.28	12	864
water	language	4.26	6	424
students	characters	4.21	8	540
students	channel	4.20	8	536
species	cultural	4.17	4	259
gene	children	4.14	6	378
online	muscle	4.10	1	61
protein	communication	4.09	4	239
students	initiation	4.09	2	119
teachers	t	4.08	8	471
war	learning	4.07	4	234

Figure 3.2. Cumulative distributions of the core (median) and tail (maximum) novelty scores at the dissertation level.

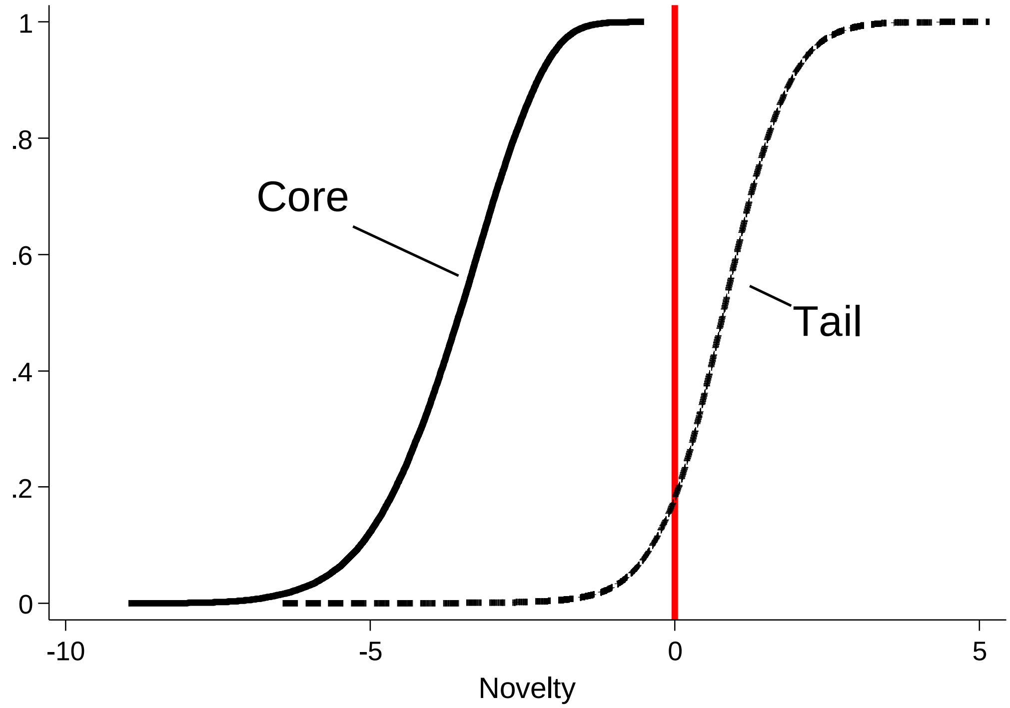

Table 3.8. Two dissertation abstracts, one with high novelty (top) and another with low novelty (bottom).

Dissertation field	Abstract
Computer Sciences	"The world is full of objects: cups, phones, computers, books, and countless other things. For many tasks, robots need to understand that this object is a stapler, that object is a textbook, and this other object is a gallon of milk. The classic approach to this problem is object recognition, which classifies each observation into one of several previously-defined classes. While modern object recognition algorithms perform well, they require extensive supervised training: in a standard benchmark, the training data average more than four hundred images of each object class. The cost of manually labeling the training data prohibits these techniques from scaling to general environments. Homes and workplaces can contain hundreds of unique objects, and the objects in one environment may not appear in another. We propose a different approach: object discovery. Rather than rely on manual labeling, we describe unsupervised algorithms that leverage the unique capabilities of a mobile robot to discover the objects (and classes of objects) in an environment. Because our algorithms are unsupervised, they scale gracefully to large, general environments over long periods of time. To validate our results, we collected 67 robotic runs through a large office environment. This dataset, which we have made available to the community, is the largest of its kind. At each step, we treat the problem as one of robotics, not disembodied computer vision. The scale and quality of our results demonstrate the merit of this perspective, and prove the practicality of long-term large-scale object discovery."
Mathematics	"Classification of "small K-types" for the connected, simply connected split real form of simple Lie type other than type C_n is obtained via Cliford algebras which completes the list of all small K-types of dim > 1 for the connected, simply connected split real form of simple Lie types. An analog, P^{xi}, of Kostant's P^{gamma} matrix is defined for a K-type V_{xi} of principalseries admitting a small K-type, and a product formula of the determinant of P^{xi} over the rank one subgroups corresponding to the reduced restrictedroots is proved. The product formula and the relationship between P{xi}and intertwining operator between the genuine principal series representations give a method to compute the shift factors of Vogan and Wallach's generalization of Leslie Cohn's determinant formula for the restriction of the intertwining operator to a K-isotypic component given in terms of ratios of classical gamma functions. The determinant of the intertwining operator between the genuine principal series representations of widetilde{SL(n,R)} (n geq 3) is obtained as a ratio of classical gamma functions."

Notes: The dissertation abstracts are quoted directly, the sources are available upon request.

Table 3.9. Predicting core and tail novelty in abstract idea combinations, by type and area of interdisciplinary members.

	Core novelty			
	(1)	**(2)**	**(3)**	**(4)**
Members	-0.014**	-0.021***	-0.022***	-0.021***
	(0.005)	(0.005)	(0.005)	(0.005)
Interdisciplinary		0.033***	0.012	0.016*
		(0.005)	(0.007)	(0.007)
Cross-area			0.037***	
			(0.008)	
From:				
Arc				-0.057
				(0.074)
A&H				-0.335***
				(0.022)
Bus				0.110***
				(0.029)
Edu				0.353***
				(0.024)
Eng				0.079***
				(0.015)
Law				-0.098
				(0.118)
LS				-0.102***
				(0.013)
HSM				0.021
				(0.019)
PSM				0.007
				(0.012)
SBS				0.228***
				(0.014)
Cons.	-3.180***	-3.169***	-3.169***	-3.136***
	(0.034)	(0.034)	(0.034)	(0.034)
Obs.	61,936	61,936	61,936	61,936
R^2	0.176	0.176	0.177	0.188

Standard errors in parentheses; *** p<0.001, ** p<0.01, * p<0.05; All models control for Ph.D. year (ref.=2010), Ph.D. area (ref.=Social & Behavioral Sciences), and Ph.D. University (ref.=UNC). Interdisciplinary members are a subset of total members and cross-area members are a subset of interdisciplinary members and they were not removed from the larger set in these regressions.

Table 3.9 continued.

	Tail novelty			
	(5)	**(6)**	**(7)**	**(8)**
Members	-0.007	-0.014**	-0.014**	-0.014**
	(0.004)	(0.004)	(0.004)	(0.004)
Interdisciplinary		0.031***	0.018**	0.018**
		(0.004)	(0.006)	(0.006)
Cross-area			0.024***	
			(0.007)	
From:				
Arc				-0.085
				(0.064)
A&H				-0.108***
				(0.019)
Bus				-0.001
				(0.025)
Edu				0.181***
				(0.021)
Eng				0.008
				(0.013)
Law				-0.241*
				(0.102)
LS				0.009
				(0.011)
HSM				0.011
				(0.016)
PSM				-0.003
				(0.011)
SBS				0.108***
				(0.012)
	1.029***	1.039***	1.039***	1.052***
Cons.	(0.029)	(0.029)	(0.029)	(0.029)
Obs.	61,936	61,936	61,936	61,936
R^2	0.064	0.065	0.065	0.068

Table 3.10. Field specific effects of interdisciplinarity on core novelty in abstract idea combinations.

	Arc	A&H	Bus	Edu	Eng	Law
No. members	0.150	0.035*	-0.012	-0.028	-0.028*	0.249
	(0.123)	(0.016)	(0.029)	(0.019)	(0.012)	(0.331)
No. i.d. memb.	-0.463*	-0.087***	0.007	0.066**	0.043**	0.534
	(0.210)	(0.020)	(0.062)	(0.024)	(0.014)	(0.353)
No. cross-area members from:						
Arc	NA	0.458	-0.167	-0.142	-0.013	
	NA	(0.293)	(0.447)	(0.219)	(0.180)	
A&H	0.271	NA	-0.303	-0.307***	-0.211	0.137
	(0.299)	NA	(0.181)	(0.051)	(0.112)	(0.433)
Bus	1.066*	0.605**	NA	-0.008	0.227**	-0.463
	(0.455)	(0.190)	NA	(0.088)	(0.080)	(0.566)
Edu	0.023	0.765***	0.016	NA	0.316***	
	(0.590)	(0.072)	(0.102)	NA	(0.090)	
Eng	0.643*	0.316	0.031	-0.101	NA	
	(0.276)	(0.171)	(0.099)	(0.090)	NA	
Law	1.343	0.731	-0.252			NA
	(1.010)	(0.404)	(0.855)			NA
LS	0.449	0.433***	-0.078	-0.147*	-0.068**	
	(0.256)	(0.091)	(0.220)	(0.072)	(0.024)	
HSM	0.676	0.486**	-0.031	-0.160*	-0.162***	0.278
	(0.491)	(0.188)	(0.128)	(0.074)	(0.045)	(1.157)
PSM	0.463	0.218*	-0.084	-0.068	-0.008	
	(0.319)	(0.093)	(0.085)	(0.059)	(0.018)	
SBS	0.550*	0.389***	-0.037	-0.112**	0.231***	
	(0.234)	(0.034)	(0.069)	(0.036)	(0.046)	
Cons.	-3.281***	-4.890***	-2.964***	-2.488***	-3.550***	-4.152**
	(0.749)	(0.104)	(0.184)	(0.120)	(0.135)	(1.431)
Obs.	206	8,080	1,920	4,156	10,507	35
R^2	0.369	0.083	0.063	0.035	0.018	0.347

Standard errors in parentheses; *** p<0.001, ** p<0.01, * p<0.05; All models control for Ph.D. year (ref.=2010) and Ph.D. University (ref.=UNC). NAs along the diagonal indicate that these cells cannot be estimated by definition. Empty cells do not have enough observations and are omitted. Interdisciplinary members are a subset of total members and cross-area members are a subset of interdisciplinary members and they were not removed from the larger set in these regressions, i.e., if a dissertation had five members, two of whom were interdisciplinary and one of whom was cross-area, then the counts for these variables would be members=5, interdisciplinary=2, cross-area=1.

Table 3.10 continued.

	LS	HSM	PSM	SBS
No. members	-0.030*	-0.039*	-0.021	-0.043***
	(0.013)	(0.020)	(0.012)	(0.011)
No. i.d. memb.	0.013	0.087	0.106***	0.051**
	(0.013)	(0.048)	(0.019)	(0.018)
No. cross-area members from:				
Arc	-0.227	0.754	0.087	-0.291*
	(0.175)	(0.718)	(0.159)	(0.146)
A&H	0.084	-0.386*	0.115	-0.479***
	(0.092)	(0.182)	(0.099)	(0.029)
Bus	0.010	-0.104	0.330***	-0.047
	(0.191)	(0.125)	(0.085)	(0.041)
Edu	0.420***	0.263**	0.435***	0.152***
	(0.119)	(0.089)	(0.074)	(0.036)
Eng	0.041	-0.172*	0.071**	-0.111
	(0.031)	(0.072)	(0.024)	(0.059)
Law			-0.979	-0.241
			(1.064)	(0.126)
LS	NA	-0.271***	-0.144***	-0.175***
	NA	(0.054)	(0.026)	(0.035)
HSM	-0.015	NA	0.113*	0.071
	(0.029)	NA	(0.053)	(0.042)
PSM	0.080***	-0.146*	NA	-0.139***
	(0.023)	(0.064)	NA	(0.036)
SBS	0.341***	0.203***	0.214***	NA
	(0.033)	(0.061)	(0.036)	NA
Cons.	-3.873***	-3.392***	-3.600***	-2.931***
	(0.083)	(0.115)	(0.079)	(0.071)
Obs.	9,008	3,479	12,045	12,500
R^2	0.040	0.127	0.034	0.067

Table 3.11. Field specific effects of interdisciplinarity on tail novelty in abstract idea combinations.

	Arc	A&H	Bus	Edu	Eng	Law
No. members	-0.085	0.012	0.008	-0.015	0.035**	0.246
	(0.142)	(0.013)	(0.037)	(0.026)	(0.013)	(0.238)
No. i.d. memb.	-0.092	0.050**	-0.031	-0.025	-0.040**	0.712*
	(0.241)	(0.016)	(0.079)	(0.033)	(0.015)	(0.255)
No. cross-area members from:						
Arc	NA	-0.056	-0.305	0.119	0.490**	
	NA	(0.238)	(0.566)	(0.297)	(0.188)	
A&H	-0.227	NA	0.134	0.318***	0.022	-0.014
	(0.342)	NA	(0.229)	(0.070)	(0.116)	(0.312)
Bus	0.471	0.203	NA	0.039	0.558***	0.033
	(0.522)	(0.154)	NA	(0.120)	(0.083)	(0.408)
Edu	1.132	0.228***	-0.141	NA	0.341***	
	(0.676)	(0.059)	(0.129)	NA	(0.093)	
Eng	-0.075	0.293*	0.438***	0.195	NA	
	(0.316)	(0.139)	(0.126)	(0.122)	NA	
Law	-0.004	0.114	0.054			NA
	(1.159)	(0.328)	(1.081)			NA
LS	0.189	0.061	0.174	0.147	0.363***	
	(0.293)	(0.074)	(0.279)	(0.098)	(0.025)	
HSM	0.591	0.207	0.128	0.259**	0.326***	1.506
	(0.563)	(0.153)	(0.162)	(0.100)	(0.047)	(0.834)
PSM	-0.127	0.284***	0.168	0.137	0.039*	
	(0.366)	(0.075)	(0.107)	(0.080)	(0.019)	
SBS	-0.248	0.044	-0.049	0.244***	0.617***	
	(0.269)	(0.028)	(0.088)	(0.049)	(0.048)	
Cons.	-3.016***	-4.504***	-4.431***	-4.430***	-3.756***	-5.140***
	(0.860)	(0.085)	(0.233)	(0.163)	(0.141)	(1.032)
Obs.	206	8,080	1,920	4,156	10,507	35
R^2	0.260	0.031	0.081	0.034	0.075	0.557

Standard errors in parentheses; *** p<0.001, ** p<0.01, * p<0.05; see notes to table 3.10.

Table 3.11 continued…

VARIABLES	HSM	PSM	SBS
No. members	0.015	-0.025*	0.007
	(0.019)	(0.013)	(0.012)
No. i.d. memb.	-0.024	0.057**	0.125***
	(0.048)	(0.019)	(0.020)
No. cross-area members from:			
Arc	0.235	0.245	-0.143
	(0.714)	(0.165)	(0.157)
A&H	0.153	0.444***	-0.161***
	(0.181)	(0.103)	(0.031)
Bus	-0.059	0.533***	-0.222***
	(0.125)	(0.088)	(0.044)
Edu	0.222*	0.680***	-0.032
	(0.088)	(0.077)	(0.039)
Eng	0.220**	0.077**	0.146*
	(0.071)	(0.025)	(0.063)
Law		-0.072	-0.150
		(1.106)	(0.135)
LS	-0.071	0.248***	0.161***
	(0.054)	(0.027)	(0.038)
HSM	NA	0.255***	0.142**
	NA	(0.055)	(0.045)
PSM	-0.034	NA	0.150***
	(0.063)	NA	(0.039)
SBS	0.272***	0.458***	NA
	(0.060)	(0.038)	NA
Constant	-4.157***	-4.381***	-4.164***
	(0.115)	(0.082)	(0.076)
Observations	3,479	12,045	12,500
R-squared	0.083	0.064	0.030

CHAPTER 4: INTERDISCIPLINARY OR MULTIDISCIPLINARY? FIELD BASED SEGREGATION AND COLLABORATION AT THE POPULATION ASSOCIATION OF AMERICA, 2002-2014.

Introduction

Federal funding agencies, academic administrators, and others seeking to advance the progress of scientific research are increasingly promoting interdisciplinarity (Brint et al. 2009; Jacobs and Frickel 2009; National Academy of Sciences 2004). These recent efforts follow on a longstanding academic debate advocating the benefits of interdisciplinarity (Campbell 1969; Klein 1990). In this paper, I present a case study of interdisciplinarity in the contemporary field of demography. Demographers have long focused on topics of interest to multiple fields, and they are frequently trained in disciplinary fields (i.e., sociology, economics, etc.) as opposed to within specific demography departments. Indeed, at least in the United States, there are very few departments of demography. As such, the field of demography represents a blind spot for the study of interdisciplinarity. Most researchers evaluate the interdisciplinarity of a field on the basis of its curricular offerings, defining fields characterized by interdisciplinarity as "degree-granting programs that draw on faculty from more than one academic department" (Brint et al. 2009:160). Others distinguish disciplines as fields which have internal labor markets, where a large proportion of those trained in the discipline are hired by other departments within the discipline (Abbott 2001; Jacobs 2014). Lacking departments and degrees, however, it is challenging to evaluate demography's interdisciplinarity according to these definitions. This is reflected in prior work: a large classificatory study of field-level interdisciplinarity by Brint et al. (2009) makes no mention of demography one way or the other[6]. One of the most puzzling features of the field of demography is that it exhibits many of the features of a discipline – a long history, a core group of self-describing members, national and regional professional associations, and dedicated journals – coupled with a relative lack of institutional representation in terms of departments and degree programs that would maintain an internal labor market. Put simply, demography is a unique field.

A number of other interesting features make demography an excellent case study of interdisciplinarity that has the power to illuminate unaddressed issues in the study of contemporary research organizations. First, demographers are not exclusively employed within academic contexts; rather, a substantial number of core demographers (i.e., those who are publishing) work for government organizations or non-profits. Prior studies of interdisciplinarity have neglected researchers not working at universities, despite the substantial numbers of such researchers in several fields thought to exhibit high interdisciplinarity (e.g., public health, public policy, education). Examining the integration of a field that includes such individuals has the potential to reveal a different pattern of disciplinary fault lines than might be seen within academic institutions, because non-academic institutions are not typically organized into departmental structures with disciplinary labor markets, which leads them to have different orientations towards research risks and payoffs (Evans 2010a; Evans 2010b). Examining such a field also speaks to broader movements in academic policy circles to pursue greater integration between universities and other research entities (e.g., the "triple helix" model of university-

[6] There are more explicit demography programs in Europe than the United States, but these are outside the scope of Brint and colleagues' project and have not, to my knowledge, been formally counted.

government-industry collaboration; Etzkowitz and Leydesdorff 2000). Second, fields of research are not nationally bounded, though most studies of interdisciplinarity have looked within a national context. A substantial portion of core demographers are trained and based in non-U.S. institutions. By looking at these individuals, I provide a fuller picture of the integration of global research with that based in the United States and how interdisciplinarity complements these patterns. Third, demography as a field garners a higher level of federal funding than many others, certainly among the social sciences. This makes its relationship to interdisciplinarity especially important to understand, because federal funders are some of the largest backers of interdisciplinarity. A field as dependent on research funding as demography is may be more receptive to the push for interdisciplinarity than other fields such as the many "studies" programs that have received the bulk of the interdisciplinarity literature's attention but which receive less research funding (e.g., American studies, women's studies, and African-American studies [Jacobs 2013; Rojas 2007]).

Finally, while there are few demography departments, there are several research centers devoted to the study of demography (e.g., the Carolina Population Center at U. NC-Chapel Hill, the Office of Population Research at Princeton U., etc.). Research centers have received substantial attention in recent work on interdisciplinarity and variants of the research center model used in demography have been offered as an alternative and potentially superior approach to institutional efforts to instill interdisciplinarity through curricular offerings or the creation of new departments (Jacobs 2014; Jacobs and Frickel 2009). A field's potential to create interdisciplinarity through research centers and in the absence of institutional structures like programs and departments thus fills an important gap in the literature, and, I argue, comes closer to the espoused agenda of interdisciplinarity, which is to avoid cases where "the interdisciplinary impulse finally does not liberate us from the narrow confines of academic ghettos to something more capacious; it merely redomiciles us in enclosures that do not advertise themselves as such" (Fish 1989:18). Indeed, it is puzzling that successful interdisciplinarity would be defined as a field donning the departmental trappings of a discipline by acquiring curricular and departmental structures, as many prior analyses of interdisciplinarity have assumed (Brint et al. 2009; Abbott 2001; Jacobs 2014; Jacobs and Frickel 2009; Klein 2010; Klein 1990; Sá 2008)[7]. An analysis of the role of research centers in creating interdisciplinarity in the field of demography will help to ground broader arguments about the limits of disciplinary integration that can be achieved through the research center mechanism.

Demography's interdisciplinarity is, of course, also of interest to demographers. The questions pursued in this paper have received attention for as long as the field of demography has existed in the United States. The founding of the Population Association of America (PAA), the field's primary scholarly association[8], in 1931 was marked by conflict between those interested in affecting policy (especially reproductive policy) and those with more scholarly interests (Hodgson 1983; Notestein and Osborn 1971). Discussions of the field's early evolution in the 1930s-1950s have noted its "two main foci, one in the biological sciences and the other in the social sciences" (Notestein 1982:651). Concerns about the field's disengagement with mathematics, statistics, biology, and economics and its domination by those trained in sociology appeared as early as the first published issue of the journal *Demography*, in 1964 (Blake 1964). Interviews with PAA presidents across multiple decades into the 1990s make note of important

[7] For instance, some argue that successful interdisciplinary programs "have a core faculty with full-time appointments located entirely or partly within a program" (Klein 2010:106).

[8] Though there are several international demography organizations, most notably the International Union for the Scientific Study of Population (IUSSP), I focus on the PAA because the PAA meets annually whereas the IUSSP meets every four years.

contributions to the field from sociologists, statisticians, economists, geographers, and, more recently, those in schools of public health and medicine, but they also note tensions between these groups (History Committee of the Population Association of America 2015). A notable moment of concern over the field's interdisciplinarity is marked by the reactions to a special issue published in 1989, "Demography as an interdiscipline" (Stycos 1989), which two reviewers criticized because all contributors to the volume, except for one social anthropologist, were sociologists (Compton 1990; Guest 1990). The long history of debate over the field's orientation and questions about interdisciplinarity in demography provide an intriguing backdrop to the contemporary case. Pessimism about the future of the demography's disciplinary integration remains, with some calling it "a doughnut of a field, without a center" (Lee 2001:1), others stating "as an intellectual endeavor it seems to be advancing into vagueness" (McNicoll 2007:613), and still others complaining it is "becoming fragmented, compartmentalized from inside" (Tabutin and Depledge 2007:23). However, similar concerns have existed almost as long as the field has been in existence, yet the field has persisted and even grown over the decades.

How should we evaluate the interdisciplinarity of demography? Interdisciplinarity can be conceptualized along a spectrum of disciplinary integration (Jacobs 2014). At the lowest level, there "is the slightest form of cross-disciplinary linkage", multidisciplinary research, where a mélange of similar topics are grouped together (Jacobs 2014:77; Klein 2010). Next comes interdisciplinary work, which is "interactive, collaborative, and sometimes 'proactive'" and characterized by hybridization and cross-fertilization (Jacobs 2014:77). Interactions and collaborations are key features that distinguish interdisciplinary work from multidisciplinary work. Finally, in the rarest form of interdisciplinarity, true synthesis is obtained in transdisciplinary work, which brings together research from multiple fields to provide new intellectual syntheses and solutions to practical problems while at the same time changing understandings in the fields from which those solutions originated[9]. Interdisciplinarity, thus, ranges from multidisciplinary engagement to interdisciplinary interaction and, potentially, transdisciplinary synthesis.

Where does contemporary demography fit along the spectrum of interdisciplinarity? Are demographers an integrated group of researchers from multiple disciplinary backgrounds solving population problems in conjunction with one another? If so, what is the nature of this integration? If not, are the fields which contribute to demography engaged in parallel play, interested in what those in other fields are doing and sometimes responsive to them, but not interacting with them in a coordinated fashion? In what direction is the field of demography heading? These questions draw an analogy with the literature on racial segregation (Reardon and Firebaugh 2002). A common problem in that literature is one of scale (B. A. Lee et al. 2008; Reardon et al. 2008; Reardon and O'Sullivan 2004). At one level of aggregation (e.g., census tracts), an area may appear racially integrated because individuals of multiple races live there, while a lower level of aggregation (e.g., census blocks) might show higher rates of segregation as people sort themselves within the larger unit (Iceland and Steinmetz 2003). A related concern is seen in the literature on racial segregation in schools: schools may be integrated in the sense of an even racial mix, but students of different races rarely associate with one another in classes, clubs, or through friendship (Moody 2001; Mouw and Entwisle 2006). American demography may have members who were trained in multiple fields, but it is unknown whether these

[9] I cannot distinguish interdisciplinary research from transdisciplinary research because I focus on one field, American demography. Without considering what occurs in other fields, transdisciplinarity cannot be distinguished from interdisciplinarity in Jacobs' hierarchy.

members collaborate with each other across disciplinary boundaries creating interdisciplinary synthesis, or else if they remain segregated within the field in a multidisciplinary manner.

To address these questions, I look at the Ph.D. granting departments of current core demographers and how fields of training pattern the research that is being authored and presented. In light of the previous commentary, I consider co-authorship as a hallmark of interdisciplinary integration, while I take less direct engagement between fields, such as working on similar topical areas or subtopics, as evidence of multidisciplinary engagement. I also investigate the possibility of an even lower level of integration, which would be characterized by substantial disciplinary reproduction within the subfields of demography. Co-authorship between members of different fields is, of course, a proxy for true synthesis and engagement, with variable veracity from paper to paper and author to author, but I assert that it reflects greater interdisciplinary engagement than simply working on topics that draw the attention of members of other fields. At a minimum, coauthors take each other's ideas, expertise, and experience into consideration as they craft a manuscript. I define core demographers as those who are listed in multiple years on papers presented at the PAA's annual meeting.

Looking at meaningful units – like collaborations on papers, the co-appearance in sessions where the work of scholars from multiple fields may be heard, or working on similar broad topical areas or subtopics – is an important focus that helps to distinguish interdisciplinary interaction from multidisciplinary engagement. In the first section of this paper, I give an overview of the history of the PAA and its annual meeting and elaborate on the benefits and limitations of using it as a sampling frame to define the population of core demographers. Next, I discuss the data and methods used to characterize whether demography is an interdisciplinary or multidisciplinary field. The first set of results I present are compositional, describing the fields in which contemporary demographers earned their Ph.D.s and how these fields overlap with major topical areas in demography (e.g., fertility, mortality, etc.). This helps to establish if demography can even be considered a multidiscipline, or whether its members self-segregate into topical areas on the basis of their backgrounds. I also look at co-appearance in the same sessions, which are more refined units than the large topical groupings in demography. If demographers are not sorted into topical areas on the basis of their disciplinary backgrounds but are sorted on such a basis into sessions, this would be consistent with a multidisciplinary orientation of the field, albeit one which has room to further integrate.

The second set of results describes the collaboration structure of the field on the basis of coauthored papers. Such collaboration networks capture "the informal interaction structure" that is critical to the process and progress of scientific research (Moody 2004:214) as well as to the professional identity of researchers. I look at the extent to which co-authorship takes place between core demographers with the same disciplinary background compared to between those with different disciplinary backgrounds. I also provide more detailed investigations into the specific patterns of cross-disciplinary co-authorship, highlighting which fields tend to co-author together more or less frequently. This approach aligns with those looking at broader maps of science, as well as those who examine subfield integration within specific disciplines like sociology (e.g., Leahey and Moody 2014). Here, however, I employ measures of segregation likely to be familiar to many demographers. The approach I use cannot capture all aspects of interdisciplinarity – for instance, it ignores the institutionalist aspects pursued by Brint et al. (2009) – but it contributes a meaningful dimension whose methodological and theoretical underpinnings facilitate the comparison of demography with analyses of other fields, like sociology (Moody 2004).

The Population Association of America

The Population Association of America (PAA) is the professional organization of American demographers, promoting research on population issues with a global focus and membership. Founded over several months from December, 1930 to May, 1931, its purpose was to develop an American institution for population work similar to those in Europe affiliated with the International Union for the Scientific Study of Population (IUSSP), which grew out of the World Population Conference in Geneva in 1927 (Notestein 1973:7 quoted in History Committee of the Population Association of America 2015). There was initial controversy over whether the PAA's promotional work would be scholarship or activism over birth control. The scholars won out with the withdrawal of Margaret Sanger's nomination as the Association's first vice-president. Sixty seven individuals attended the first annual PAA meeting in New York City in April, 1932 (Weeks 2014). Except for early years when the IUSSP was meeting and while meetings were suspended during World War Two, the organization has held an annual meeting each year since then.

The number of PAA members has grown substantially since the PAA was founded, as shown in Figure 4.1. According to interviews with early PAA presidents, nearly all of PAA's members attended the annual meeting from its founding until about 1960 (History Committee of the Population Association of America 2015). The organization was geographically centralized at first: eight of the first 20 meetings were hosted by the Office of Population Research at Princeton University in Princeton, NJ and all but one of them were on the east coast (three each in New York and Washington, D.C., two in Chapel Hill , and one each in Atlantic City, Charlottesville, Philadelphia, and Cincinnati/Miami, Ohio). The early years of the organization were marked by important foundation and industry funding; indeed, the organizing meeting that led to the formation of the PAA was funded by the Milbank Memorial Fund while the first American delegation to the IUSSP was funded by the Metropolitan Life Insurance Company (Notestein 1973 in History Committee of the Population Association of America 2015). Biographies of early association presidents make clear that there were a substantial number of career opportunities in non-governmental organizations, industry, and government posts: e.g., after receiving his Ph.D. in 1927, Frank Notestein worked with the Millbank Memorial Fund from 1928-1936, then began a professorship at Princeton, then took part time leave to be Consultant-Director of the United Nations Population Division from 1946-1948, returned to Princeton, then became the Population Council's president in 1959 until he retired in 1968 (History Committee of the Population Association of America 2015). Despite this biography, Notestein considered himself more of an academic than many of his contemporaries who had similarly complex résumés (History Committee of the Population Association of America 2015), moving between university professorships, companies, research organizations, and federal statistical agencies with a frequency that is rare in the current academic community. Though questions about fertility control dominated some of the early controversies in the association, there was also substantial work on migration, mortality, population projection, genetics and other topics (C. Taebur 1973 in History Committee of the Population Association of America 2015).

Most of the early members of PAA focused on demographic topics and concerns in the United States, but after World War Two the focus shifted to encompass a substantial amount of research in international settings. This outward turn coincided with worldwide concern over high levels of fertility and rates of population growth, as well as additional foundation support aimed at providing demographic training to members of non-U.S. countries, especially those in the developing world. The Ford Foundation, Population Council, and the University of Chicago provided some of the first fellowships explicitly for foreign scholars, with an aim to train demographers from other countries who would then return to their countries and found a population center. This program realized early successes with the founding of the Population Institute of the Philippines at the University of the Philippines in Manila in 1964, followed shortly thereafter by the establishment of the Population Institute at Chulalongkorn at the University of Bangkok and then others in Indonesia and India (Hauser 1988 quoted in History Committee of the Population Association of America 2015). The “missionary” approach to demographic training adopted by key members of the early PAA and funding organizations greatly enhanced the global capacity for conducting demographic research.

Some portion of the internationalization of demographic training and research in the 1960s can be seen in the membership and meeting attendance trajectories showcased in Figure 4.1. Beginning in the early 1960s, levels of membership in the organization began to diverge from the numbers of meeting attendees, though both grew at substantial rates. At the same time, the annual meeting began to be held in non-East Coast locations, including Chicago and San Francisco. The growth in membership slowed in the 1970s, but attendance levels continued to rise. Starting in the 1980s, the pace of growth in PAA membership began to rise at the same levels as the pace of growth in meeting attendance. As of January, 2015, the high water mark in PAA attendance was reached in 2011 at the Washington, DC meeting while the greatest level of association membership was recorded in 2014, in Boston, MA.

A Sampling Frame for Demographers

There are currently over 3,400 members of the PAA, of whom 2,168 attended the recent annual meeting in Boston and 1,878 of whom were listed as authors on paper presentations. The organization's present size suggests a markedly different regime than the one that existed even twenty years ago, when the PAA meetings were called "a big family reunion" (Guest 1994:88), given that attendance has since doubled. As the organization grows in scale, there may be more opportunities for fields to self-segregate. This "population growth" may have changed the structure of the field, and coincided with a substantial influx of health scholars, but it also complicates the measurement of interdisciplinarity as changes in scale complicate the measurement of segregation. Nonetheless, the first challenge is defining the population at risk, an ironic question given the field's focus on denominators and risk sets.

How do we enumerate the population of demographers? Three approaches are immediately apparent. First, one could survey the large demographic training programs (housed in the major population research centers), but there is turnover in which are funded and focusing on them would inappropriately privilege academic settings and, among those, the ones that are large and well-funded. A second approach would sample demographers on the basis of the journals they publish in. However, demographers publish in increasingly diverse outlets (Van Dalen and Henkens 2012), so sampling only authors who publish in *Demography* or the handful of other "core demography" journals (e.g., *Population and Development Review, Population Studies*) would provide a narrow and biased sample that misses researchers in fields which do not tend to publish in those outlets (e.g., anthropology, public health). Broadening the search to other journals, a difficult task in itself[10], would include a large proportion of non-demographers

[10] ISI Web of Science lists an improbable 363 source titles that publish articles in the subject area "demography".

who would be challenging to screen from the sample without some other point of reference. The third approach is to sample on the basis of membership in, or research engagement with, one of the professional organizations representing demographers, as Van Dalen and Henkens did with the IUSSP. I focus on researchers who are actively engaged in research that is presented at the annual meetings of the PAA.

I define the population of core demographers based on research participation at the annual meeting of the PAA, specifically focusing on core demographers listed as authors on papers presented at multiple PAA meetings over the period 2002-2014. Using these criteria, I found 1,837 core demographers. I argue that focusing on individuals listed on papers presented at multiple PAAs gives a more accurate picture of who constitutes contemporary demographers than other approaches, such as sampling from journals, can offer. Research presented at conferences tends to be closer to the research that is actually being conducted at a given time than work which appears in publications, which have long and varying lag periods from the time of submission to appearing in print. A focus on the primary annual meeting of demographers is also important because the establishment and maintenance of a national meeting is frequently noted as a key marker of the success of an interdisciplinary field (Jacobs 2014:135). Examining the patterns of co-authorship amongst individuals at these meetings allows me to characterize the contemporary integration of the field because co-authorship necessitates collaboration, which may or may not be interdisciplinary. By contrast, a multidisciplinary group of authors working on the same topical areas can more easily fail to engage with each other, instead relying on different perspectives, theories, methodologies and background literature about the same topic (compare, e.g., the economic treatment of immigration to the sociological). Owing to issues of data availability, I focus on the years 2002-2014, which has the advantage of adding a contemporary perspective on the field to prior reports as well as adding the possibility of trend analysis, which has not hitherto been done in a quantitative approach. The history of the association suggests that recent years may be different than past ones owing to the much larger size of the organization, both in terms of membership and in terms of meeting attendance levels. For instance, there was a 39% increase in PAA attendance between 2002 (1,558 attendees) and 2014 (2,168 attendees).

Additional Considerations

The PAA meeting is organized in a somewhat unique way compared to other annual meetings in the social sciences. For instance, a substantial portion of sessions at the American Sociological Association's annual meeting is organized around a theme by the incoming president, while the remaining sessions are organized autonomously by the more than 100 sections to which members of the association can belong. PAA, by contrast, has lots of involvement from the membership. It is organized by an army of volunteer session chairs who consider competitive paper submissions. Very few of the sessions at PAA are invited sessions, where papers are not selected through a competitive process. Indeed, the entire annual meeting information system architecture was run from 2002-2015 on the PAMPA software system voluntarily provided by German Rodriguez, whose consistent coding enabled the data collection for this paper. This organizational model gives substantial leeway to the membership in determining what sessions are held and which papers are presented, which may enable greater disciplinary segregation in terms of paper selection if session chairs have a tendency to select papers authored by members of their own field, for instance. In addition, over the period of study, PAA has had a rule that members can only appear on the program twice. The specific applications of this rule varied over time and there are a few exceptions, but generally this means that individuals do not appear more than twice as authors of papers in a given year. I investigate the sensitivity of my results to using a different source of data (Web of Science) about co-authorship patterns below and find few meaningful differences. Of course, it is impossible to tell with such a case study whether the results presented here are a consequence of the specific process that leads to the PAA's annual meeting or whether they owe to specific tendencies in the field of demography, but I argue that they are, nonetheless, important for demographers to be aware of.

Attention to the contemporary PAA annual meetings has other advantages as well. First, it allows me to examine whether and how the organization of the field's research topics, which are reproduced in the structure of the annual meeting along topical lines, is patterned by the disciplinary backgrounds of its members. Demography is known to have a diversity of research topics (e.g., fertility, mortality, and migration), and it may be that researchers from different disciplinary backgrounds work on these topics at different rates. This possibility was suggested in the introduction to the aforementioned "Demography as an interdiscipline", which noted the field "drawing heavily on biology and sociology for the study of fertility; on economics and geography for studies of migration; and on the health sciences for analyses of mortality" (Stycos 1989). Rather than viewing the mapping of disciplinary backgrounds to topical areas in demography as indicating interdisciplinary synthesis, however, I view such mapping as a very low level of integration, even lower than multidisciplinarity. If fields are essentially reproducing themselves within the topical subfields of demography, with little engagement in the topical areas by demographers trained in different disciplines, then this would be inconsistent with any sort of synthesis. At the annual meeting, session chairs accept papers into sessions with given titles and agendas, but the sessions are grouped into larger topical areas. Over the period of analysis in this paper, 2002-2014, the major topics changed slightly, but most of these changes were semantic (e.g., the topic "Children and Youth" was called "Children, including Child Health, Youth and Parenting" in 2008 only), or involved the merging of small topical areas, such as when "Applied Demography" and "Other Topics" were combined into a single group in 2014. In total, I have identified 11 stable topics at PAA. Table 4.1 shows these assigned topics and the program-listed topics they were derived from. Do the 11 stable sub-fields at PAA map onto the disciplinary origins of scholars working in those fields? I add this consideration to my examination of interdisciplinarity in the whole field's composition and its collaboration network. In both sets of analyses, I pay attention to recent and emerging trends.

I investigate the role of training centers in bridging the field of demography. Specialized training is a key mark of the professionalization (and disciplining) of a field that is achieved by institutions, which, in the field of American demography, are most often the large population centers embedded within research universities. The field of demography has been characterized as being highly integrated because of its training mechanisms. Guest (1994) notes the particular role of large population centers in determining these trends, with "most participants claiming some relationship to the major demographic centers" (Guest 1994:88) and a labor market structured around these centers: "Usually, the demographic shops have a star researcher who sets the tone for research and training. Faculty and students have frequently collaborated on research topics, with many resulting coauthored papers. Many newly minted Ph.D.s from these programs have been traded with other shops, either as faculty members or post-docs, and many of the Ph.D.s have been sent out to other sociology departments (the 'provinces') to serve as their token demographers" (Guest 1994:87). Whether this twenty-year old perspective remains true is an open question.

As with any field, there are major intellectual currents and thus thought leaders in contemporary demography. A survey of 970 demographers who were members of the IUSSP conducted in 2009 found high levels of consensus on the primary population problem of the day, said to be population aging (Van Dalen and Henkens 2012). Van Dalen and Henkens (2012) also asked respondents to name the (living or deceased) demographers who "have been the most important in making demography what it is today" and "have been the most important for your own work" (Van Dalen and Henkens 2012:391). Respondents could choose from a list of 250 highly cited and well known demographers, or could write in their own responses. The top 5 most frequently nominated demographers accounted for 35% of the total votes, a level which the authors argue is comparable to what has been found in other well-defined disciplines like sociology. The modally named researchers were not sociologists, however: Caldwell (Ph.D. in Demography), Bongaarts (Ph.D. in Physiology and Biomedical Engineering), Coale (Ph.D. in Economics), and Brass (Ph.D. in Statistics) were in the top five most often named in both lists. Whether the field is integrated by collaboration with these types of star demographers – a hub structure in the network sense – is unknown, however.

Demography has been described as "a coauthoring field" (Menken 1988:213 quoted in History Committee of the Population Association of America 2015), a theme repeated throughout the *PAA Oral History Project* interviews. However, few studies have looked explicitly at its level of co-authorship. The most prominent is a content analysis of papers appearing in the journal *Demography*, which found that over its first 29 years of publication, from 1964-1993, 45% of articles in the journal were coauthored, with a 26% increase in co-authorship rates over the study period (Teachman, Paasch, and Carver 1993). Teachman and colleagues attribute this trend to funding patterns and the rise of large population centers, an argument echoed in other reflections on the field (Guest 1994). Another report compares the composition of collaborations in *Demography* to what is seen in the field of Ancient History, which has markedly lower collaboration rates, and found that demographers' collaborations tend to be more insular than ancient historians with respect to within-country collaboration but more expansive in terms of the academic rank differences between authors such that demographers "almost seem to avoid collaborating with colleagues in the same rank" (Hin 2013:8). Unfortunately, neither report addresses the disciplinary composition of the field of demography or the configuration of its constituent fields with respect to each other in the co-authorship network, though they both note that the rise of research teams in demography seems to be related to methodological and substantive specialization. For a field like demography, however, it is unclear whether an analysis of cross-disciplinary co-authorship patterns in the leading journal could shed much light on the question of its interdisciplinarity because of the aforementioned challenge of defining the population at risk: what journals should be included? Certainly *Demography* would be included, but is that representative enough of the publication outlets pursued by demographers? Some economics departments, for instance, heavily disincentivize their members from publishing in journals like *Demography*. Missing data and false positives are especially perilous for the methods of network analysis (Kossinets 2006; Laumann, Marsden, and Prensky 1989; Smith and Moody 2013). Looking at a more carefully targeted set of core demographers has the potential to improve on prior studies of the field's level of co-authorship.

Data and Methods

I test whether American demography is an interdisciplinary field characterized by co-authorship between people of different disciplinary backgrounds or a multidisciplinary field characterized by members of different fields working separately on similar topics. I also explore the possibility of an even lower level of integration. To evaluate this, I look at the population of core demographers who have been listed as authors on papers presented in three or more years between 2002-2014 at the Population Association of America. I begin with a descriptive analysis of co-authoring levels and a compositional analysis of the entire field with respect to the disciplinary diversity of its members and the subfields they pursue. This establishes the interdisciplinarity of demography as a field but does not resolve whether it is interdisciplinary or multidisciplinary. To distinguish between these possibilities, I look at co-authorship patterns and segregation. I focus on collaborations across authors' Ph.D. fields and how this varies by topical subfield in demography.

Data

I collected data from the annual meeting website of the Population Association of America for all available years (2002-2014). For each year, I recorded the author list, title and abstract of every paper presented in regular sessions. I exclude poster sessions to maintain an eligibility criteria that is constant over the period (there was variability over the period in poster acceptance criteria). This approach gives a census of all individuals who were listed on papers presented at PAA any time over the 13 year period of study; individuals who only served as session chairs or discussants, or were listed only on poster presentations, are excluded. Table 4.2 shows these data. There were 8,322 unique individuals listed as authors on papers presented at PAA over this time frame, who together yielded 19,546 unique author-paper records (an average of 2.3 records per person). I define the focal population as the 1,873 individuals who authored papers presented in three or more years, who in total contributed 11,142 author-paper records (an average of 6.1 records per person). I chose a cutoff of three years because those listed on papers in only one or two years tend to either be graduate students who have not obtained their Ph.D.s yet, or else they are not yet fully integrated into the field. While there are interesting questions to be asked about the socialization of new members into the field of demography, they are beyond the scope of this paper which focuses on disciplinary segregation among core demographers. Those who attend PAA in three or more years, by contrast, are more likely to be committed to membership in the field. Though restricting analyses to those who attend three or more times causes me to exclude a few key demographers, including a former president of PAA, I argue that this choice is sensible because it restricts the analysis to the core population of demographers.

I use the full data set (including core and non-core demographers) to construct a co-authorship network. In this network, I represent each author who is listed on a paper presented at PAA from 2002-2014 as a node. I create a link between individuals if they are co-authors on at least one paper presented at PAA and weight the link by the number of papers that they coauthored over the period of study. Figure 4.2 shows the largest connected subset (component) of this co-authorship network and the population of demographers who have attended three or more times ("core demographers", in red) and fewer than three times (in blue). As can be seen, the set of core demographers is drawn from all over the network: some are peripheral, while others are at the center[11]. In total, the network of demographers is moderately well connected: the largest component shown in Figure 4.2 contains 67% of the demographers identified (listed

[11] Though core has a specific meaning in the networks literature, I rely here on the more informal notion of it. In a coauthorship network such as this, a person can be centrally located if they appear on a paper with other centrally located individuals, as would a graduate student with multiple core authors, which accounts for why so many blue nodes are in the center of the graph.

on a paper presented at PAA over the study period). A substantial share of the non-connected portion of the network owes to the large proportion (11%) of individuals who had no coauthors over the entire period. An additional 18% were in components with fewer than five other individuals, probably representing single papers that were not linked to the large subset in the co-authorship network. The two appearance rule enforced by the PAA, discussed above, may impact these patterns somewhat, and I investigate the sensitivity of my results to this by using an alternative data source described in detail below. On average, people had 3.5 coauthors, while the maximum number was 41. Average numbers of coauthors varied substantially across the major Ph.D. fields of core demographers, the collection and coding of which I discuss below. The ranking is as follows (with average number of coauthors in parentheses): psychology (2.3), history (2.5), geography (3.0), anthropology (3.1), business and economics (3.3), sociology (3.3), demography (3.3), medicine (3.6), public health (3.7), formal sciences (3.8), public policy (4.3), social work (5.2), and other (5.3).

For each core demographer, I collected three focal pieces of information, if available: Ph.D. field, Ph.D. granting university, and year of Ph.D. attainment. Each case was searched carefully using online search engines and other sources. If a CV or an academic or other organizational website was not available, I recorded the relevant information from one of the following sources: biographical notes on a website, public LinkedIn account information, by examining the relevant pages of their dissertation if it was indexed in ProQuest’s Dissertations and Theses database (ProQuest 2015), or other sources such as listings of advisee degrees and years on advisor’s CVs. When any information was available, I recorded it, so some cases have Ph.D. fields but not universities or years as well as other combinations.

A reassuringly large proportion of cases have Ph.D. information available. Table 4.3 shows the number of people who have attended the PAA various numbers of years and the percent of cases in those years where I could find their Ph.D. information. In general, the coverage is high; I was able to find Ph.D. field and university information for more than 85% of all targeted cases (Ph.D. year information was more challenging to find). I coded Ph.D. fields into a limited number of categories based on their frequency in order to make the analysis more tractable. The translation between the categorical groupings I used and the actually listed Ph.D. fields is shown in Table 4.4. I consider individuals with joint demography degrees – e.g., sociology and demography, or demography and economics – to be trained in the non-demography field – e.g., sociology or economics. I only considered degrees whose title explicitly and uniquely focused on demography or population studies to be demography degrees. This may be a controversial decision, however, as shown later, there are meaningful differences between those trained in stand-alone demography departments vs. those trained in joint programs with other fields.

Figure 4.3 reconsiders the co-authorship network of demographers shown in Figure 4.2 from the perspective of the fields in which demographers were trained. In it, I have shrunk the size of the nodes of non-core demographers (those who were listed on PAA papers in fewer than three years who were shown in blue in Figure 4.2 and are excluded from subsequent analyses but presented here to show the full architecture of the co-authorship network) so that they do not obscure the general disciplinary patterns. Core demographers are color coded according to the field groups in Table 4.4. As can be seen, there is a substantial portion of sociologists (in red), who tend to be near the center of the network, while economists (in green), public health researchers (in yellow), and others tend to be more peripheral. In addition to the general patterns, however, there is a substantial amount of mixing where even the portions of the network most dominated by sociologists have links to other fields. To assess this quantitatively, I turn to more precise measures described below.

As discussed above, PAA has a two appearance rule that prohibits individuals from appearing on any given year's final program in more than two places. This rule may bias measurement of the co-authorship network and analyses of collaboration across fields. On the one hand, however, people who are listed on more than two papers would presumably take themselves off of the papers to which they have contributed the least, which might align the measurement of co-authorship more closely with the concept of collaboration. At the same time, this rule will only affect prolific individuals who may be bridging contributors across a variety of domains. Either way, because there may be concerns about the accuracy of the authorships in the PAA data because of the two appearance rule, I conduct a sensitivity analysis. To do this, I examine co-authorships in a data set of papers authored by core demographers in the Web of Science. This data set was constructed by first searching for all peer reviewed journal articles in the very broad category of social science journals found in Web of Science that were authored by anyone matching the last and first names of core demographers and which were published between 2002-2014. Any articles that were returned as part of edited volumes were discarded because these are less well covered in the Web of Science data set, as were any papers that were missing titles, journal names, or dates. I also dropped supplementary materials articles that were sometimes indexed separately from the main article (indicated by having the same title, authors, journal name, issue, etc. but different page numbers). Finally, because this sensitivity analysis focuses on co-authorships, I also discarded sole authored articles as well as those where only one author could be matched to a core demographer. These procedures allow the best possible comparison with the PAA data without unnecessarily introducing random noise.

Methods

In addition to the descriptive questions discussed above about the disciplinary origin of current core demographers and their potential sorting into subfields within demography, I am also interested in whether the structure of collaboration in demography bridges disciplinary boundaries. The question is whether the field of demography, while drawing members from multiple disciplines and fields, may be subdivided internally into non-overlapping clusters of disciplinarily trained researchers. Such a structure, if it exists, would be evident in the co-authorship network. To test for it, I first consider whether there is even descriptive evidence of co-authorship clustering by field of Ph.D. origin.

I begin by examining the observed-expected ratios (OERs) by major groups of fields listed in Table 4.4. The network data used allow me to construct a "mixing matrix" which cross-classifies co-authorships by the respective Ph.D. fields of their constituents (Morris et al. 2009). This approach necessitates dropping individuals who never appear as coauthors; there were 276 of these individuals among the core demographers. I measure OER as $OER_{ij} = \ln\left(o_{ij}/e_{ij}\right)$, where o_{ij} is the observed number of co-authorships between people with Ph.D.s in field *i* and *j* and $e_{ij} = \left(\sum_i o_{ij} \sum_j o_{ij}\right)/\sum o_{ij}$, which reflects the expected number of collaborations between members of those fields under conditions of independence. Values greater than zero indicate that there are more collaborations than would be expected by chance, i.e., that there is more interdisciplinarity than expected, while values below zero indicate less collaboration than would be expected under conditions of statistical independence. The OER is a selection coefficient which measures proportionate deviation from what would be expected given population composition and co-authorship rates by Ph.D. field. Other variants of this measure are widely employed in the networks literature (Leahey and Moody 2014; Schilling and Green 2011; Uzzi et al. 2013).

In addition to looking at OERs at the level of papers, I also consider them at the level of PAA sessions – groups of about four papers presented in a cohesive block of time in a year. Here, I use the same definition for OERs as above but replace co-authorships with co-session appearances. Looking at session-level OERs will help to contextualize how frequently authors from multiple fields appear in the same session together; that is, whether an economist author of one paper, for instance, is likely to hear a paper with an author who was trained as a sociologist. Because sessions by design have multiple papers and therefore multiple authors in them, this analysis does not restrict the sample to coauthored papers only.

Next, I turn to measures of segregation. Of the many available measures, I focus on one that outperforms all others when individuals come from more than two groups (Reardon and Firebaugh 2002). This measure is the Information Theory Index (H), which is a disproportionality based measure (though it also measures other aspects of segregation such as association and the diversity ratio) and tends to be strongly correlated with the more familiar dissimilarity index. It is defined as $H = \sum_{m=1}^{M} \sum_{j=1}^{J} \frac{t_j}{TE} \pi_{jm} \ln \frac{\pi_{jm}}{\pi_m}$, where m indexes the M fields, j indexes the J papers or sessions, t_j is the number of individuals on paper or session j, T is the total number of cases, π_{jm} is the proportion of individuals in field m on paper or session j, π_m is the proportion in group m, and $E = \sum_{m=1}^{M} \pi_m \ln\left(\frac{1}{\pi_m}\right)$ is Theil's entropy index (Reardon and Firebaugh 2002). The information theory index can be interpreted as the ratio of within-unit diversity to total diversity; in other words, it measures how much less diverse papers or sessions are than core demographers at PAA as a whole. H ranges from 0 (minimum segregation) to 1 (maximum segregation) when every paper or session's set of authors come from a single field (B. A. Lee et al. 2008; Reardon et al. 2008; Reardon and O'Sullivan 2004). As with OERs, I compute H using both co-authorships on papers as well as co-appearances in the same session.

Another way to look at the functional integration of the field of demography is to examine how closely what is being researched mirrors the collaboration networks of who is doing this research. To explore this, I consider the 11 broad and stable groupings of PAA sessions discussed above and enumerated in Table 4.1. This gives a different perspective on integration than can be seen with co-authorship because it embeds the social production of knowledge (co-authorship) in an explicit idea space of substantive research areas (session groupings). This links to Abbot's ideas about the structural vs. cultural aspects of disciplines (Abbott 2001). I propose to examine this with segregation measures for more than two groups. Just as different racial groups can be sorted in different ways between neighborhoods depending on the scale of the analysis, so too can demographers of different fields be sorted into PAA subfields.

Results

I first consider the composition of current core demographers. Table 4.5 shows the disciplinary origin of the 1,575 core demographers for whom I was able to obtain information on their Ph.D. field, with fields defined as per Table 4.4, as well as the proportion of people in each field who were trained outside of the U.S. and in two separate definitions of the major population research centers. As could be anticipated from the collaboration network shown in Figure 4.3, nearly half (47%) of core demographers were trained in a sociology program (or perhaps a joint sociology/demography program). Though there is a general sense that sociologists dominate demography's population composition in the literature that has been noted many times throughout history (Blake 1964; Stycos 1989), the extent to which this is true has not been quantified to the best of my knowledge. Training in a sociology program is the modal background for core demographers, but this is true for less than half of them. The second most prominent Ph.D. field among core demographers is economics, with 18% of core demographers having been trained in economics programs. Demography itself (or population studies, etc. as described in Table 4.4), constitutes the third most prevalent training program with 11%. The remaining origin fields are all small, with public health (6%) and public policy and political science (4%) being the most notable.

Overall, 16% of core demographers obtained their Ph.D. outside of the United States. This proportion varies substantially by sub-field, however, though the numbers are quite small. Those with degrees in mathematics, statistics, physics, and engineering are the most likely to have been trained outside of the U.S., followed by geographers and environmental researchers and those in the medical fields. Depending on which definition of population research centers is used (APC or NICHD see the table's notes), around two thirds of core demographers were trained in population research centers; because those trained in foreign institutions are not considered at risk of being trained in an NICHD funded or APC affiliated population center, approximately three quarters of those who obtained their Ph.D.s in U.S. institutions were trained in population centers (72% in NICHD centers and 83% in APC centers, a statistically significant if not particularly meaningful difference).

I next consider how demographers are sorting themselves into the topical subfields of demography. Table 4.6 shows the total and Ph.D. field specific percentage of appearances by core demographers in each of the PAA's topical subfields. Starting with the total across all Ph.D. fields, we can see that the topical subfield with the most author appearances is Health and Mortality. A portion of this likely reflects higher co-authorship rates in that subfield and the fact that Health and Mortality (18%) and the Fertility, Family Planning, Sexual Behavior, and Reproductive Health (17%) have the most author appearances (they also have the most sessions and papers at PAA, especially in recent years). The third most author appearances are found in the Marriage, Family, Households, and Unions subfield (14%). Sections with the fewest author appearances include Population, Development, and Environment (4%), Appplied Demography and Other Topics (5%), Data and Methods (5%), and Population and Aging (5%).

Sociologists tend to appear evenly across the topical subfields; in no case do they have a larger than 3% deviation from the global average percentage in a topical field across all core demographers. Thirteen percent of economists's appearances are in the Economy, Labor Force, Education, and Inequality section, which is a 6% deviation from the average core demographer (who appeared in this subfield 7% of the time). Those trained in stand-alone demography programs appear substantially more often in the Fertility section, and they also tend to appear less frequently than the average demographer in the Children and Youth and Marriage sections. Those in public health appear 14% more frequently in the Fertility topic (likely because it contains reproductive health) and the health topic, and tend to appear less frequently than the average demographer in the Economy, Marriage, and Migrations sections. In all, there is an incredibly strong χ^2 association between fields of Ph.D. and appearance in sections. This indicates that demographers are engaged at a level more consistent with multidisciplinarity than something less than that, because researchers from many disciplinary backgrounds work on the diverse set of topics of interest to demographers.

With these compositional tendencies established, I now examine the collaboration structure. I begin by considering fields which tend to collaborate with each other more and less frequently than would be expected under conditions of independence. To do this, I consider OERs, defined above, which can be interpreted in a similar fashion to a logit coefficient, where positive values indicate greater than expected collaboration between individuals in the row field and the column field and negative values indicate less. Because of the small cell sizes and the amount of information, I only focus on collaboration rates between the largest five Ph.D. fields. Table 4.7 shows this information for co-authorship (top) and co-appearance in the same sessions (bottom). Ph.D.s from the same field tend to coauthor with each other more than would be expected by chance, but there is considerable heterogeneity in this tendency. Those with Ph.D.s in public health, followed by those with economics degrees, are the most insular in terms of co-authorship. Sociologists uniformly coauthor less than would be expected with individuals with Ph.D.s in the other fields, while those with Ph.D.s in public policy tend to coauthor with everyone (except sociologists) at higher than expected rates. Economists coauthor less than would be expected with everyone except those with public policy degrees, likely reflecting the substantial number of economists who hold positions in public policy departments. The largest divide in the table is between those with sociology degrees and those with economics degrees. Similar, but more muted patterns can be seen in the session co-appearance portion of the table.

Next, I turn to issues of segregation in the field. Here, I focus on trends in the information theory index in PAA co-authorships, co-appearances in sessions, and in the topical subfields. I complement this analysis with a sensitivity test looking at co-authorships on papers indexed in

Web of Science. Figure 4.4 shows these results. Most strikingly, there are no meaningful trends over the past 13 years in segregation rates. Co-authorship at PAA tends to be highly segregated by Ph.D. field, and the sensitivity test with Web of Science data confirms this tendency. To put this in perspective, the H index of White-Black segregation (the largest amount) in census tracts in the 40 largest metropolitan areas of the United States in 2000 was 0.418 (Reardon et al. 2008). Indeed, the most segregated metropolitan area in the United States in the 2000 census, Gary, IN, had a white-black segregation ratio of 0.767 when H is computed with 500 meter person-specific neighborhoods (B. A. Lee et al. 2008); multi-group measures almost always yield even lower levels of segregation. Thus, coauthored papers written by core demographers are substantially more segregated by their Ph.D. fields than even the most racially segregated cities. Table 4.8 shows the segregation levels taken across all years decomposed by the topical subfields and presented for sessions and co-authorships. It also offers the same comparisons amongst the five largest Ph.D. granting fields as well as all fields. Generally, the results are quite similar across these fields and do not substantially change the interpretations of Figure 4.4. In other words, no topical subfield tends to be substantially less segregated than the others.

However, there is good news: PAA sessions are less segregated than coauthored papers, and the overall level of segregation by PAA's major topical sections, previously explored in Table 4.6, is substantially lower than that. In other words, while core demographers may not work in interdisciplinary teams, the sessions their papers appear in tend to have other papers authored by people of a more diverse set of disciplinary backgrounds. There is even less segregation in terms of the major topical subfields. Furthermore, there is no evidence of increasing segregation or disciplinary fragmentation, at least over the last 13 years. Another way to help understand these patterns can be found in the literature on spatially dependent segregation, where authors tend to use a ratio of macro to micro segregation, which shows how much small environment segregation is dependent on large environment segregation (B. A. Lee et al. 2008; Reardon et al. 2008). This interpretation does not map directly onto the concepts of papers, sessions, and topics, but it is still useful in understanding the relationships between these nested entities.

Computing these ratios across all years, where H is 0.7668 for PAA co-authorships, 0.6104 for session co-appearances, and 0.0560 for topical subfields, yields the following conclusions. Were every PAA session able to be turned into a single paper – i.e., if the authors could all coordinate to work on a composite paper – then this would only reduce field based segregation by 20% ($1 - 0.6106/0.7668$). However, if the topical subfields were themselves papers, then this would reduce field based segregation by 91% ($1 - 0.0560/0.7668$). The scale invariance of the information theory index permits these types of comparisons regardless of the number of people in each group. In other words, while demographers do not sort themselves on the basis of their disciplinary backgrounds at the level of broad topical areas, they do sort themselves substantially within those areas, albeit less than they do with respect to co-authorship. This means that the field has multidisciplinary tendencies, but methodological, theoretical, and other reasons keep researchers from interacting at the level of true synthesis. Of course, these are unrealistic objectives, but they do offer some intriguing potential policy mechanisms that the PAA could pursue to increase interdisciplinarity, which I discuss below.

Conclusion

Is demography an interdisciplinary or a multidisciplinary field? That is, is it characterized by co-authorship between scholars with different disciplinary backgrounds or is demographic research produced by members of different fields working separately on similar topics? This question has substantial relevance in the current research climate where federal funding agencies, university administrations, and others are advocating for greater interdisciplinarity. It also has important ramifications for some demographers who tend to be pessimistic about the future of the field and who fear that it will "collapse and that the fragments would be recovered by other powerful neighboring disciplines" (McNicoll 2007:613). By understanding the disciplinary integration of contemporary demographers, and trends in this integration, we can obtain a benchmark by which to judge the likelihood of these scenarios.

However, measuring who is a demographer is in itself a challenging task. I began by delineating a set of core demographers sampled from those listed on papers presented at the largest and most significant annual professional meeting of demographers, the annual meeting of the PAA. I examined the composition of these contemporary core demographers in terms of the fields in which they received their Ph.D.s. Sociologists form the backbone of this group, accounting for 47% of contemporary core demographers. Economists and those trained in business schools form the second largest group with 18% representation. People trained in stand-alone demography departments are the third largest group, constituting 11%. All other fields are quite small, and represent coarser groupings (e.g., Public Policy *and* Political Science, all of the various fields of Public Health, etc.). I also demonstrated that most core demographers, at least those who were listed on papers presented at the PAA annual meeting in three or more years, received their Ph.D.s from institutions in the United States. However, a perhaps surprising 14%

were trained in non-U.S. institutions, reflecting the field's international scope. Of those trained in the United States, and of all demographers by implication, the vast majority received their Ph.D.s from institutions with population research centers. I found some evidence that demographers sort themselves into topical groups on the basis of their Ph.D. fields, though this was not an overwhelming association (despite its strong statistical significance).

In addition to this compositional analysis, I also conducted a relational analysis focused on collaboration rates between individuals as a function of their disciplinary backgrounds. Surprisingly, I found that those in public health tend to be the most predictable in terms of their appearance in specific types of sessions and in terms of their insularity with respect to co-authorship (they co-author with other public health scholars at much higher than expected rates. I also found that sociologists collaborate with other fields at universally less than expected rates, and I documented a particularly large chasm between sociologists and economists in terms of their collaboration rates. I next investigated segregation patterns by Ph.D. field, finding that, were demography a city and Ph.D. fields racial groups, it would be the most segregated city in the United States. Throughout my analyses, I attempted to look for trends, but there were none to be found. The state of contemporary demography does not seem to be changing in the last decade and there are few major differences in levels of co-authorship between its subfields.

Demographers who participate in the annual meetings of the PAA may be a special case, but they are instructive for the study of interdisciplinarity for a number of reasons. For one, focusing on the population of core demographers which participates in the annual meetings of the PAA allowed me to examine a group of researchers that was not bounded by national borders or employment at academic institutions. Most studies of interdisciplinarity look only at researchers in universities within a specific national context. Demography is a unique field in that its members do not tend to be located in stand-alone departments or programs, thus this case study provides an interesting comparison to other studies of interdisciplinary fields that tend to have their own program (e.g., women's studies). Demography is also a comparatively well-funded field, amongst those the social sciences at least, which would be expected to make it more receptive to interdisciplinary impetus of funding agencies. Finally, demographers tend to be affiliated with large population research centers, which have been offered as a model for increased interdisciplinarity in recent studies. All of these reasons would suggest that the interaction structures of demography would be particularly interdisciplinary, but this is not what I found.

Taken together, these results suggest that demography is firmly a multidisciplinary field rather than an interdisciplinary field, because its members do not strongly segregate on the basis of disciplinary background into topical areas, but they do segregate in terms of co-authorship and even on the basis of the more narrow topics on which specific sessions focus. However, there does not seem to be any tendency towards disintegration. This can be seen in the broad stability of the segregation measures over time in Figure 4.4, as well as the long persistence of demography in the face of questions about its viability. In addition, the results in this paper offer some potential ways in which interdisciplinarity of the field could be enhanced. One solution would be to make a more concerted effort to de-segregate the sessions. In examining macro-micro ratios of session level segregation to paper level segregation, only a twenty percent reduction in segregation rates could be achieved if all authors on papers in a session instead wrote a single paper together; another way to think about this is that the PAA sessions are only 20% more diverse than coauthored papers. Put another way, disciplinary segregation in PAA sessions is still comparable to the levels of racial segregation seen in the United States' most segregated cities. This means that sessions are not selecting disciplinarily diverse papers. An explicit attempt to promote greater disciplinary representation in sessions might not succeed, but it may be worth a try. Of course, whether this would reduce paper level segregation is another question altogether. However, under the current regime, if the authors of PAA papers attended the sessions in which their papers were accepted, they would not be very likely to hear the work of someone from a different disciplinary background. If demographers are to listen to each other in a meaningful way, and thereby achieve the talking across fields that is the goal of interdisciplinarity, they first need to hear each other.

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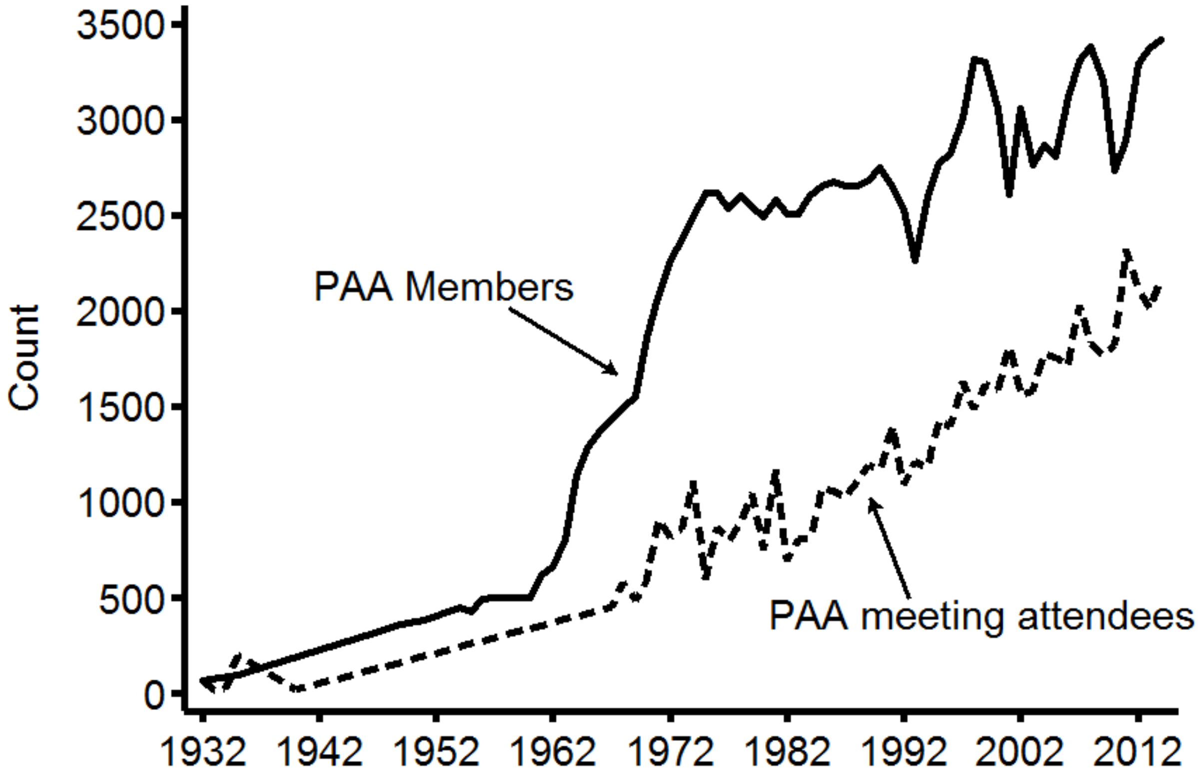
Figure 4.1. Trends in PAA membership and annual meeting attendance, 1932-2014.



Sources: members and attendees data from Weeks (2014).

Table 4.1. Assigned and program-listed topics in the data set, 2002-2014.

Assigned topic	Program listed topic
Applied Demography and Other Topics	
	Applied Demography
	Other Topics
	Other Topics (New Orleans and Katrina, Hist. Demography, and other topics)
	Applied Demography/Other Topics
Children and Youth	
	Children and Youth
	Children, including Child Health, Youth and Parenting
Data and Methods	
	Data and Methods
Economy, Labor Force, Education, and Inequality	
	Economy, Labor Force, Education, and Inequality
	Labor Force, Education, Inequality and Policy
Fertility, Family Planning, Sexual Behavior, and Reproductive Health	
	Fertility, Family Planning, and Reproductive Health
	Fertility, Family Planning, Sexual Behavior, and Reproductive Health
Gender, Race, and Ethnicity	
	Gender
	Race and Ethnicity
	Race, Ethnicity, and Gender
	Race, Ethnicity, Gender and Religion
	Gender, Race, and Ethnicity
Health and Mortality	
	AIDS
	Health and Mortality
	Adult Health, Mortality and Biology
Marriage, Family, Households, and Unions	
	Marriage, Family, and Households
	Marriage, Family, Households, and Unions
Migration and Urbanization	
	Migration and Urbanization
	Geography, Migration, Urbanization and Neighborhoods
	Migration, Neighborhoods, and Urbanization
	Migration and Population Distribution
Population and Aging	
	Population and Aging
Population, Development, and Environment	
	Population and Development
	Population, Development, and Environment

Table 4.2. Counts of participation levels at the PAA annual meetings.

Years listed on papers	People	Paper appearances	Appearances per person
1	5,073	5,310	1.0
2	1,412	3,094	2.2
3	676	2,286	3.4
4	343	1,595	4.7
5	250	1,496	6.0
6	178	1,312	7.4
7	126	1,095	8.7
8	92	950	10.3
9	52	612	11.8
10	54	700	13.0
11	40	622	15.6
12	19	337	17.7
13	7	137	19.6
Total	8,322	19,546	2.3

Figure 4.2. The co-authorship network of PAA participants, 2002-2014, with red nodes representing core demographers who have attended three or more times and blue nodes representing the rest.

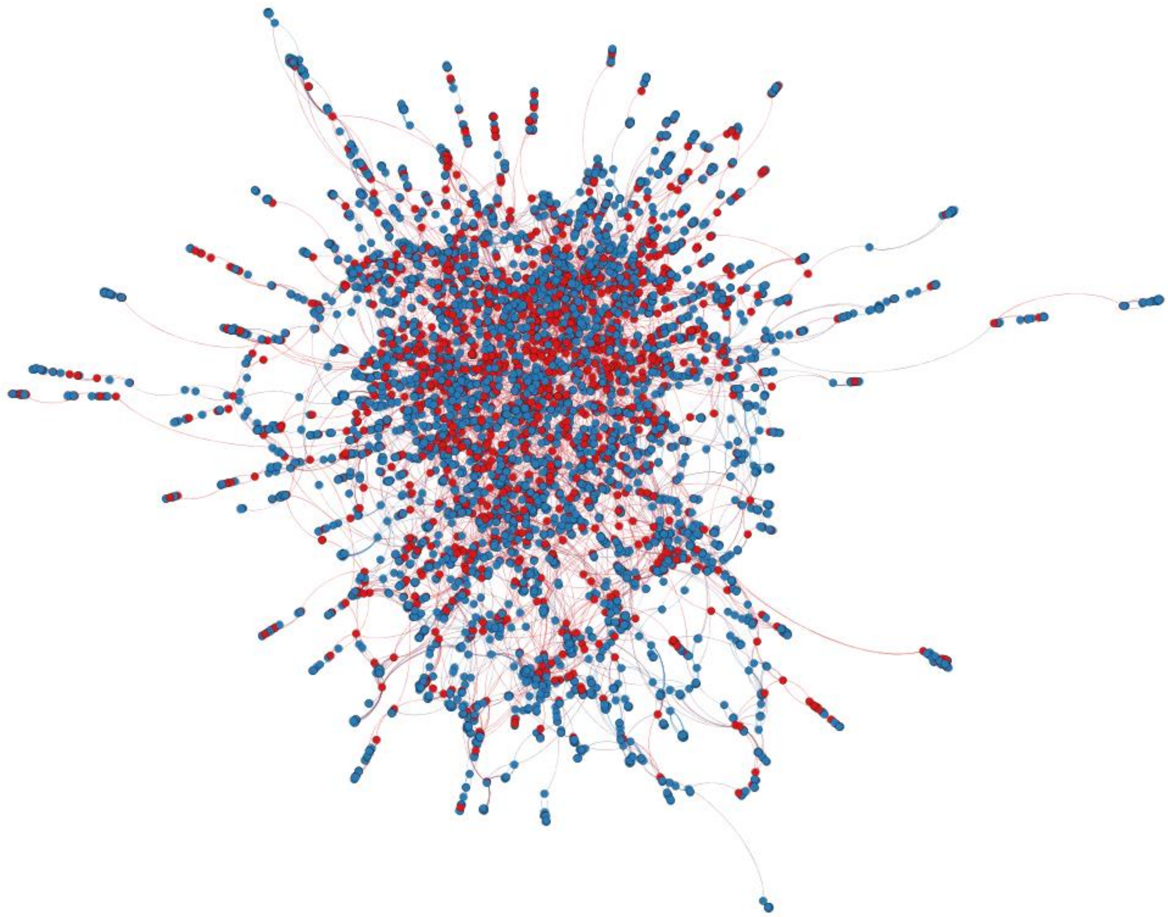


Table 4.3. Percentage of Ph.D. field, year, and university successfully coded by number of years listed on papers presented at PAA for core members.

Years listed on papers	People	Ph.D. Field	Ph.D. Year	Ph.D. University
3	676	80%	65%	80%
4	343	82%	73%	84%
5	250	81%	79%	84%
6	178	90%	84%	92%
7	126	91%	89%	95%
8	92	97%	90%	97%
9	52	96%	94%	98%
10	54	100%	98%	100%
11	40	100%	95%	95%
12	19	100%	100%	100%
13	7	100%	100%	100%

Table 4.4. Assigned fields and the degree titles that were assigned to them.

Group	Degrees included
Anthropology	anthropology; anthropology and demography; biological anthropology; cultural anthropology; medical anthropology; social anthropology; social anthropology and demography; sociocultural anthropology
Demography	demographic sciences; demography; demography and population studies; environmental demography; global health and population; historical demography; medical demography; population and development; population and public policy; population dynamics; population planning; population planning and international health; population sciences; population studies; social demography
Economics and Business	business; business administration and management; industrial relations; agricultural and resource economics; agricultural economics; agricultural economics and management; agriculture and resource economics; applied economics; applied economics and management; consumer economics; demography and economics; demography, economic development and international trade; econometrics; economics; economics and agricultural economics; economics and demography; economics and public policy; economics and sociology; family economics; family science; health economics; housing and consumer economics; international health economics; labor economics; population and health economics; social economics
Geography, Urban Planning, and Environmental Sciences	bioresource science; earth systems science; environmental science; resource management and environmental sciences; ecology; population ecology; quantitative ecology and resource management; rangeland resources; economic geography; geography; geography and demography; geography and soil science; human geography; marketing geography; population geography; spatial sciences; city and regional planning; planning; urban and regional planning; urban planning; urban planning and policy; urban systems engineering and policy planning
History	american history; economic history; history
Mathematics, Statistics, Physics, and Engineering	computer engineering; industrial engineering; mathematical engineering; physiology and biomedical engineering; theory of systems, control theory and systems analysis; mathematics; technical mathematics; mathematical cybernetics; theoretical cybernetics; physics; applied statistics; demography and social statistics; demography and statistics; mathematical statistics; research methodology; social statistics; statistical sciences; statistical sciences and demography; statistics; statistics and decision sciences; statistics and demography

Table 4.4 continued.

Group	Degrees included
Medicine, Neuroscience, Genetics, and Biology	biology; biometrics; mathematical biology; embryology; entomology; zoology; genetics; medicine; neuroscience
Other	education; education and human development; education and social policy; educational administration; literature and linguistics; linguistics; philosophy and letters; women's studies
Psychology	applied developmental and educational psychology; behavioral sciences; child psychology; clinical psychology; developmental psychology; human development and education; human development and family science; human development and family studies; human development and social policy; industrial and organizational psychology; organizational psychology; psychology; psychology and child development; social and personality psychology; social psychology
Public Health	behavioral and community health; biostatistics; biostatistics and demography; community health sciences; demography and biostatistics; demography and epidemiology; epidemiologic science; epidemiology; epidemiology and biostatistics; epidemiology and population health; epidemiology and public health; field epidemiology and biostatistics; genetic epidemiology; gerontology; gerontology and public policy; health behavior and health education; health promotion and behavior; health promotion and educational curriculum and instruction; health sciences and public health; health services and policy analysis; health services research; health services research, policy and administration; international health; international health, social and behavioral interventions program; international public health; maternal and child health; maternal child health and epidemiology; population and family health; population and family health sciences; population and health; population and international health; population health; public health; reproductive epidemiology; social epidemiology; society, human development and health
Public Policy and Political Science	demography and public affairs; demography and public policy; health policy; health policy and administration; health policy and management; policy analysis; policy analysis and management; political and social sciences; political economy and government; political economy and public policy; political science; political science, history and philosophy; public affairs; public affairs and demography; public and international affairs; public policy; public policy and management; public policy and planning; public policy and sociology; public policy studies; social policy; social policy analysis; social policy and policy analysis; social policy, planning and policy analysis
Social Work	social welfare; social work; social work and economics

Table 4.4 continued.

Sociology	criminal justice; demography and rural sociology; demography and sociology; demography, regional science, and sociology; development sociology; education policy and sociology; rural sociology and applied statistics; rural sociology and demography; social relations; social sciences; sociology; sociology and african studies; sociology and anthropology; sociology and demography; sociology and demograpy; sociology and human geography; sociology and population studies; sociology and public policy; sociology and rural sociology; sociology and social policy; sociology, population demography, and ecology; sociomedical sciences

Figure 4.3. The co-authorship network among core demographers by Ph.D. field.

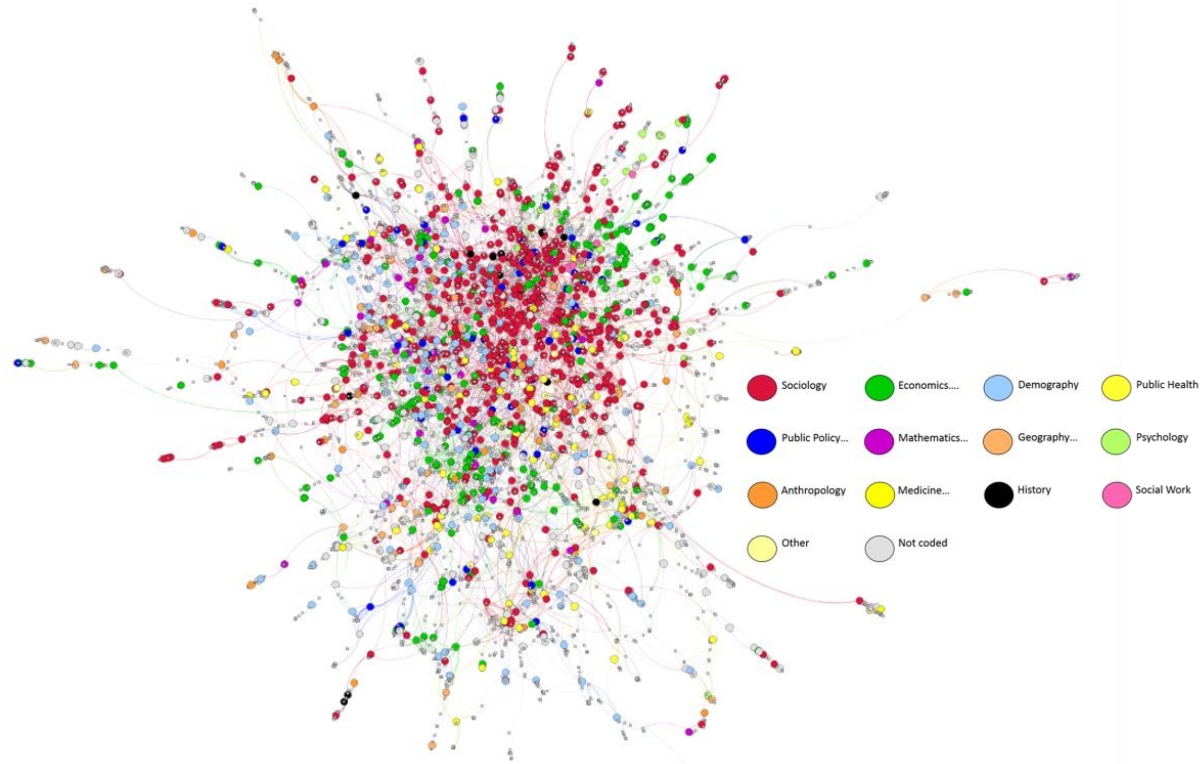


Table 4.5. Field of Ph.D. of current core demographers and foreign and population center training.

Field of Ph.D.	People with Ph.D. in field[1]		Non-U.S. Ph.D. [2]		Pop. Ctr. (APC) [2]		Pop. Ctr. (NICHD)[2]	
Sociology	741	47%	43	6%	631	85%	581	78%
Economics & Business	288	18%	36	13%	172	60%	140	49%
Demography	175	11%	83	47%	89	51%	65	37%
Public Health	91	6%	13	14%	68	75%	44	48%
Pub. Policy & Poli. Sci.	66	4%	6	9%	56	85%	45	68%
Math., Stat., Phys., & Eng.	47	3%	33	70%	9	19%	8	17%
Geog., Urb. Plan., & Env. Sci.	46	3%	23	50%	11	24%	11	24%
Psychology	36	2%	1	3%	22	61%	19	53%
Anthropology	34	2%	6	18%	15	44%	11	32%
Med., Neuro., Gene., & Bio.	18	1%	8	44%	3	17%	2	11%
History	15	1%	5	33%	8	53%	8	53%
Social Work	10	1%	0	0%	8	80%	8	80%
Other	8	1%	1	13%	3	38%	1	13%
Total	1,575	100%	258	16%	1,095	70%	943	60%

Notes: [1] percentages for this column are of the total number of coded Ph.D. obtainers; [2] the percentages in this column are the share of those with a degree in that field from the category of interest: Non-U.S. Ph.D. reflects that the Ph.D. was obtained at a university outside of the United States; Pop. Ctr. (APC) reflects Ph.D. is from a currently Association of Population Centers affiliated population center, while Pop. Ctr. (NICHD) reflects Ph.D. is from a currently NICHD funded population center.

Table 4.6. Percentage of each Ph.D. field of origin appearances in topical sessions.

	Topical subfield										
Phd.	**App**	**Chd**	**Mth**	**Ecn**	**Frt**	**Gnd**	**Hth**	**Mrr**	**Mig**	**Age**	**Env**
					Percentages						
Soci	5	10	4	7	15	8	16	17	11	4	2
Econ	3	11	4	13	13	3	15	12	10	9	7
Demo	6	5	9	3	26	4	21	9	7	6	4
PHlth	2	9	3	2	31	5	32	6	3	5	2
PPol	5	15	5	9	11	5	20	16	6	7	2
Math	5	4	18	2	25	2	22	7	3	10	2
Geog	14	2	9	2	12	5	10	5	20	5	17
Psych	2	33	2	3	15	5	12	24	1	1	1
Anth	11	4	6	4	29	8	26	3	4	2	3
Med	8	3	9	1	17	1	39	7	0	11	4
Hist	17	0	10	6	22	2	13	20	8	0	2
SW	1	34	1	12	1	5	6	36	2	0	1
Oth	6	18	3	6	27	9	9	9	9	0	3
Tot	5	10	5	7	17	6	18	14	9	5	4
					Deviations from total						
Soci	0	0	-1	0	-2	2	-1	3	2	-2	-2
Econ	-1	1	-1	6	-4	-3	-3	-2	0	4	4
Demo	1	-5	4	-4	9	-2	4	-5	-3	1	0
PHlth	-3	-1	-2	-6	14	-1	14	-8	-7	-1	-1
PPol	0	5	0	2	-6	-1	2	2	-3	1	-1
Math	0	-6	13	-5	8	-4	5	-7	-6	5	-2
Geog	9	-8	4	-5	-5	-2	-8	-9	11	-1	13
Psych	-3	23	-3	-4	-2	-1	-6	11	-8	-4	-2
Anth	6	-6	1	-4	12	2	8	-11	-5	-3	-1
Med	3	-7	4	-6	0	-5	21	-7	-9	6	0
Hist	12	-10	5	-1	4	-4	-5	7	-2	-5	-1
SW	-4	24	-4	5	-16	-1	-12	22	-7	-5	-2
Oth	1	8	-2	-1	10	3	-9	-5	0	-5	-1

Note: Full Ph.D. field and topical subfield names shown in Tables 3.4 and 3.3, respectively. Deviations are highlighted in red if they are greater than +5% and in blue if they are less than -5%.

Table 4.7. Observed Expected Ratios of Collaborations Among Five Largest Ph.D. Granting Fields.

Co-authorship of papers

	Soci…	**Econ…**	**Demo…**	**PbHl…**	**PbPo...**	**Total**
Sociology	0.3	-1.1	-0.4	-0.4	-0.2	1,435
Economics…	-1.1	1.1	-0.3	-0.6	0.2	540
Demography	-0.4	-0.3	0.9	0.6	0.4	289
Public Health	-0.4	-0.6	0.6	1.4	0.1	149
Public Policy…	-0.2	0.2	0.4	0.1	0.3	109
Total	1,435	540	289	149	109	2,522

Co-appearance in sessions

	Soci…	**Econ…**	**Demo…**	**PbHl…**	**PbPo...**	**Total**
Sociology	0.1	-0.4	-0.2	-0.1	0.0	3,326
Economics…	-0.4	0.7	-0.1	-0.1	0.0	1,166
Demography	-0.2	-0.1	0.5	0.3	0.1	757
Public Health	-0.1	-0.1	0.3	0.6	0.4	316
Public Policy…	0.0	0.0	0.1	0.4	-0.2	274
Total	3,326	1,166	757	316	274	5,839

Note: Greater than expected collaboration rates are marked with red, while less than expected rates are marked with blue.

Figure 4.4. Ph.D. field segregation in co-authorships, session appearances, and stable topic groups, 2002-2014.

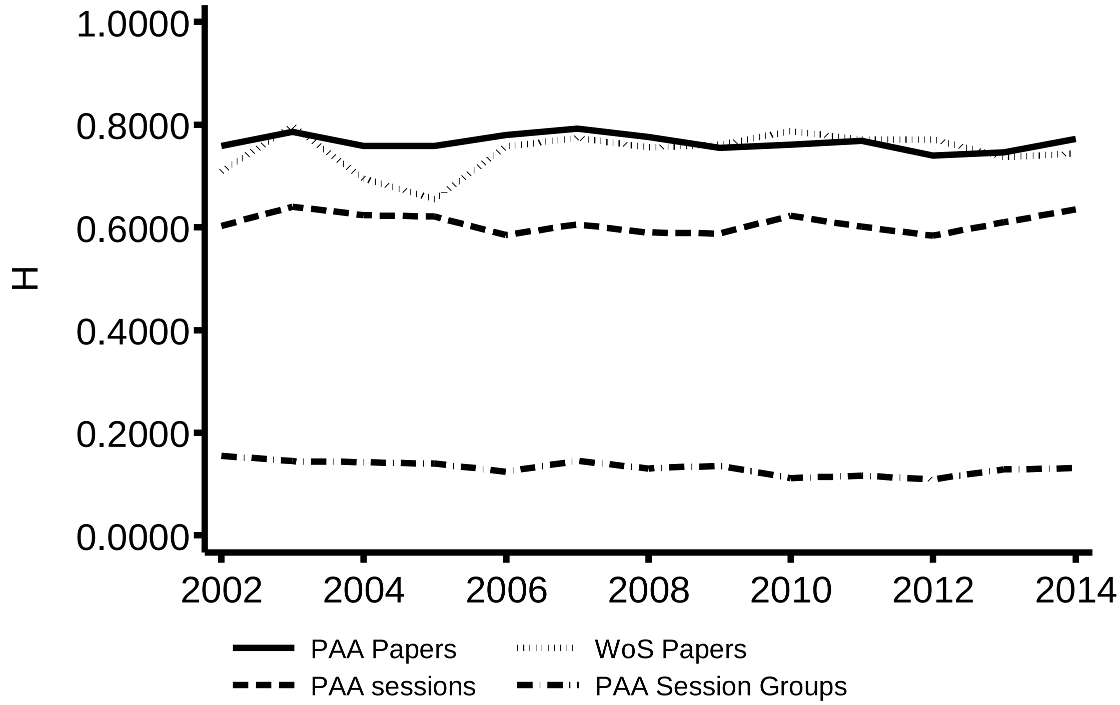


Table 4.8. Segregation indices by topical subfield.

Topical subfield	Co-authorships All	Co-authorships Big 5*	Sessions All	Sessions Big 5*
Applied Demography & Other Topics	0.7490	0.7729	0.6193	0.6583
Children & Youth	0.7678	0.7909	0.5967	0.5989
Data & Methods	0.7294	0.7023	0.5484	0.5288
Economy, Labor Force, Education, & Inequality	0.7774	0.7829	0.6057	0.5907
Fertility, Family Planning, & Sexual Behavior	0.7115	0.7048	0.5395	0.5006
Gender, Race, & Ethnicity	0.7689	0.7928	0.6320	0.6352
Health & Mortality	0.7415	0.7273	0.5739	0.5481
Marriage, Family, Households, & Unions	0.7813	0.7973	0.6093	0.5997
Migration & Urbanization	0.7943	0.7941	0.6488	0.6370
Population & Aging	0.7925	0.7881	0.6072	0.5909
Population, Development, & Environment	0.7347	0.7661	0.6017	0.6166

Note: *Big 5 indicates the 5 largest Ph.D. granting fields: Sociology, Economics and Business, Demography, Public Health, and Public Policy and Political Science.

CHAPTER 5: CONCLUSION

In this dissertation I explored three different applications that are united by a substantive theme around the way scientific knowledge is produced, organized, and changed. This work also speaks to issues of research policy, university administration, and the operation of professional academic fields. I draw on three separate sources of data. In the second chapter, I use data on funded NIH grants awarded from 1985-2013. My third chapter focuses on data pulled from dissertation committees and dissertation abstracts at 38 large universities over the period 2007-2013. The fourth chapter uses data from papers presented at annual meetings of the Population Association of America between 2002 and 2014. I approach these sources of data with tools from network and text analysis. I learned about a) the role of NIH funding in promoting research and that the doubling of the NIH budget between 1998-2003 changed the landscape of scientific research in terms of how ideas were combined in funded grant applications; b) the surprising prevalence of interdisciplinarity in the composition of dissertation committees and how cross-area faculty members serving on a dissertation committee are strongly associated with increased novelty of research conducted in dissertations; and c) how the research collaborations of contemporary demographers are organized around disciplinary origin in such a way as to suggest demography is characterized by multidisciplinary communication rather than interdisciplinary integration.

Federal funding of research and the organization of modern research universities and professional fields has received substantial attention since the 1960s (e.g., Arrow, 1962; Ben-

David and Collins, 1966; Campbell, 1969; Nelson, 1959), with renewed focus in the last twenty years (e.g., Fish, 1989; Jacobs and Frickel, 2009; Klein, 1990; Sharp et al., 2011). Many view the contemporary era as holding particular promise for large scientific breakthroughs and advances (Evans and Foster, 2011; Lazer et al., 2009; Sharp and Langer, 2011; Watts, 2012). To enable these advances, however, many optimists claim we need changes to funding mechanisms, university organization, and the operation and orientation of professional fields. Others argue that the system as it currently stands is robust, resistant to change, and successful already (Abbott, 2001; Jacobs, 2014). In this dissertation, I examine some aspects of these theoretical arguments.

The second chapter in this dissertation speaks to the role that federal funding agencies might play in pushing science forward through focused investment by examining a historical case wherein this was attempted. I looked at the doubling in NIH funding that occurred between 1998 and 2003 and found that the keywords of funded grant applications began to be used in radically different ways over this period. This chapter suggests that current calls for doubling the NIH budget again (Gingrich, 2015; Upton and DeGette, 2015) might have important effects on scientific advance. On the other hand, I did not examine other aspects of the prior doubling which seem to have had negative effects: the overproduction of Ph.D.s, increasing uncertainty in obtaining research funding, extended periods of training in the form of postdoctoral fellowships. These well-known features of contemporary scientific careers have very plausible relationships with the NIH budget doubling, because the doubling increased opportunities for scientists that later vanished. Connecting the doubling to this human toll remains a largely untold story which could be explored in later work. Greater focus on this historic event will be of great interest to policymakers, scientists, and sociologists of science.

Chapter three looks at interdisciplinarity in graduate education and research by focusing on dissertation committees. This chapter offers insight for current policy debates suggesting a push for greater interdisciplinary organization in modern research universities. I found that the majority of dissertation committees have at least one interdisciplinary member and that those dissertations which have interdisciplinary members tend to be more novel, especially if those members cross the macro-structures of scientific organization. The amount of interdisciplinarity I found in dissertation committee composition was surprising and is likely to interest scholars who argue that disciplines and fields are not isolated silos but instead have extensive cross-field communication. In other words, this finding may reassure those who argue “in defense of disciplines” (Jacobs, 2014). At the same time, the finding that dissertations with interdisciplinary members are more likely to be novel will excite those pushing for more interdisciplinarity. If interdisciplinarity has a positive association with novelty, then perhaps it should be pursued more aggressively. In either case, the results of this chapter speak to a broad audience and contribute meaningfully to the debate around interdisciplinarity.

In chapter four, I look at research collaborations among contemporary core demographers. I define core demographers according to their research participation in multiple annual meetings over the period 2002-2014 of the Population Association of America, the largest annual demography research conference. Demography as a field presents an interesting case study of interdisciplinarity. Few demographers are employed in explicit demography departments and it is rare that universities offer degrees in demography. This means that demography does not conform to the definition of disciplines or even interdisciplinary fields embraced by the institutionalist literature (Abbott, 2001; Brint et al., 2009; Jacobs, 2014), however, many demographers would argue that demography is in fact a cohesive field with its own research agenda. I found that the research collaborations of core demographers follow a pattern that is consistent with multi-disciplinarity and that there is no evidence of shifts in this tendency over the last decade and a half. This suggests that demography continues to function well – it is, in fact, a growing field in terms of numbers of journals and membership and engagement in its core organization – without embracing the model of a full-fledged discipline. This case study reveals a blind spot in the contemporary literature on interdisciplinarity and also adds additional weight to the notion that topically themed research centers are a powerful model that universities can embrace to foster greater speaking across disciplinary boundaries (Jacobs, 2014). At the same time, demographers have not achieved the level of interdisciplinary synthesis that proponents of interdisciplinarity often push, which suggests that there is additional room for improvement.

This dissertation opens several avenues to further exploration. I view each of the chapters examined here as the beginning of several projects. The first direction I intend to pursue is further analysis of the dissertation committee data. Here, my next goal is to relate the data on dissertation committee composition and dissertation novelty to data on each dissertation author's subsequent job prospects. Do those with more novel dissertations remain in academia? Do those with more interdisciplinary committees have more difficulty in obtaining jobs in their fields? Are there gender differences in these outcomes? I will pursue these and other questions by sampling individuals from the current data and attempting to find them online. If possible, I will code individuals' curriculum vitas in order to control for productivity and other factors likely to lead to academic or other jobs. By relating the composition of dissertation committees and the novelty of research pursued in the dissertation to academic employment outcomes, this project will speak to those interested in the future of the academic workforce.

A second direction I intend to pursue builds from the NIH doubling chapter. One question which interests me is whether the NIH doubling had noticeable effects on non-NIH funded research. To look at this, I will examine what happened to projects funded by the NSF and other federal agencies, whose data I have obtained from the Indiana University's Scholarly Data Base. I am also interested in exploring whether the doubling had an impact on submitted but not funded proposals. This is a central issue in determining whether the doubling changed the pool of researchers submitting grants or the novelty of submitted grants, or whether it simply enabled NIH to fund more speculative projects. Data to test these ideas exists – for instance, a recent article by Li and Agha (2015) used such data – and I will attempt to obtain it. Another way to try to obtain such data would be to work with the research offices of universities, another option I will explore in the future. A third direction I intend to explore with these data is to further tease apart how the NIH doubling achieved its goals. Were the changes confined to grants funded through a single NIH institute, or were they more broadly based? Is there a relationship between infrastructural investment at specific universities and changes in the novelty of their research grants? Many additional questions can be asked.

A final direction that I intend to pursue is to reexamine data from the fourth chapter on the interdisciplinarity of demographers with a closer eye to causal processes and a more complex social network model drawing on the exponential random graph tradition. Such analyses would allow me to better isolate whether and how network features and processes, such as triadic closure or being employed at the same institution, lead to collaboration across disciplinary lines. They would also help to clarify how academic rank, gender, and productivity structure collaborations in the field of demography and will shed further light on what demographers can do to enhance the interdisciplinarity of the field.

In summary, this dissertation represents the first steps on several related projects. I have laid the groundwork for a new research agenda built around inquiries into the production of scientific knowledge, academic collaboration, and the organization of contemporary research policy. I look forward to expanding on these goals.

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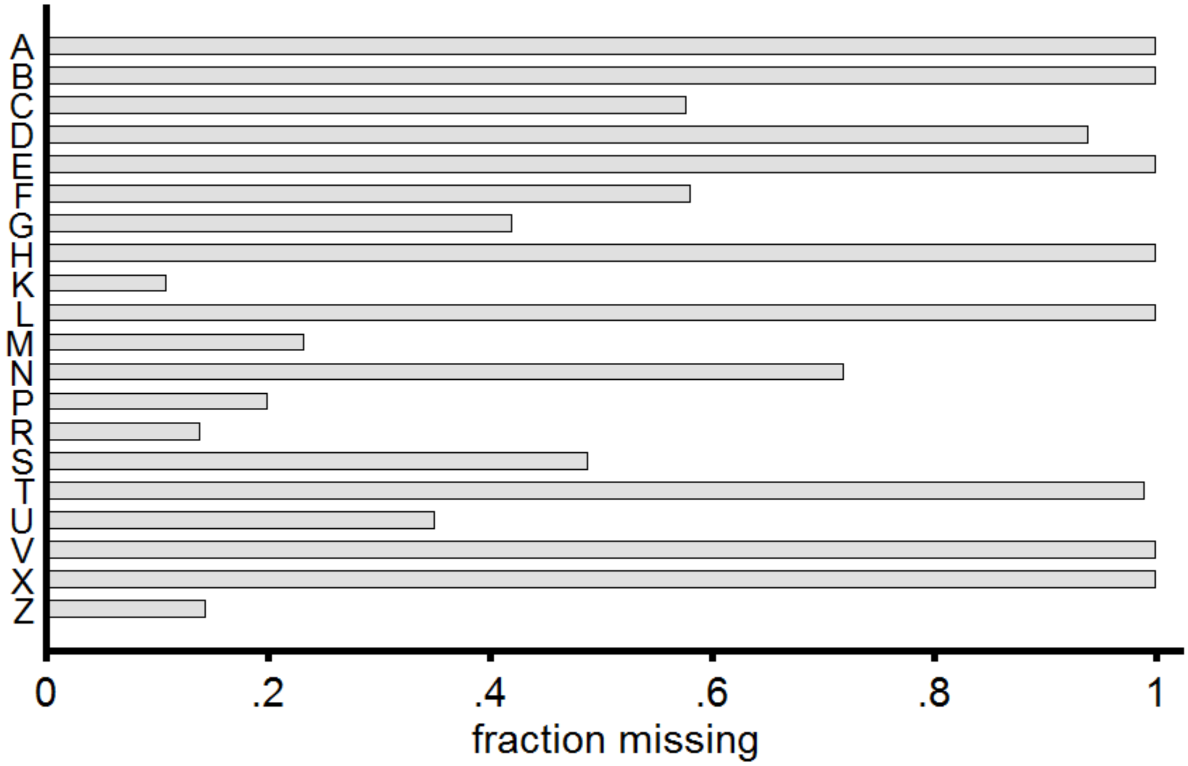
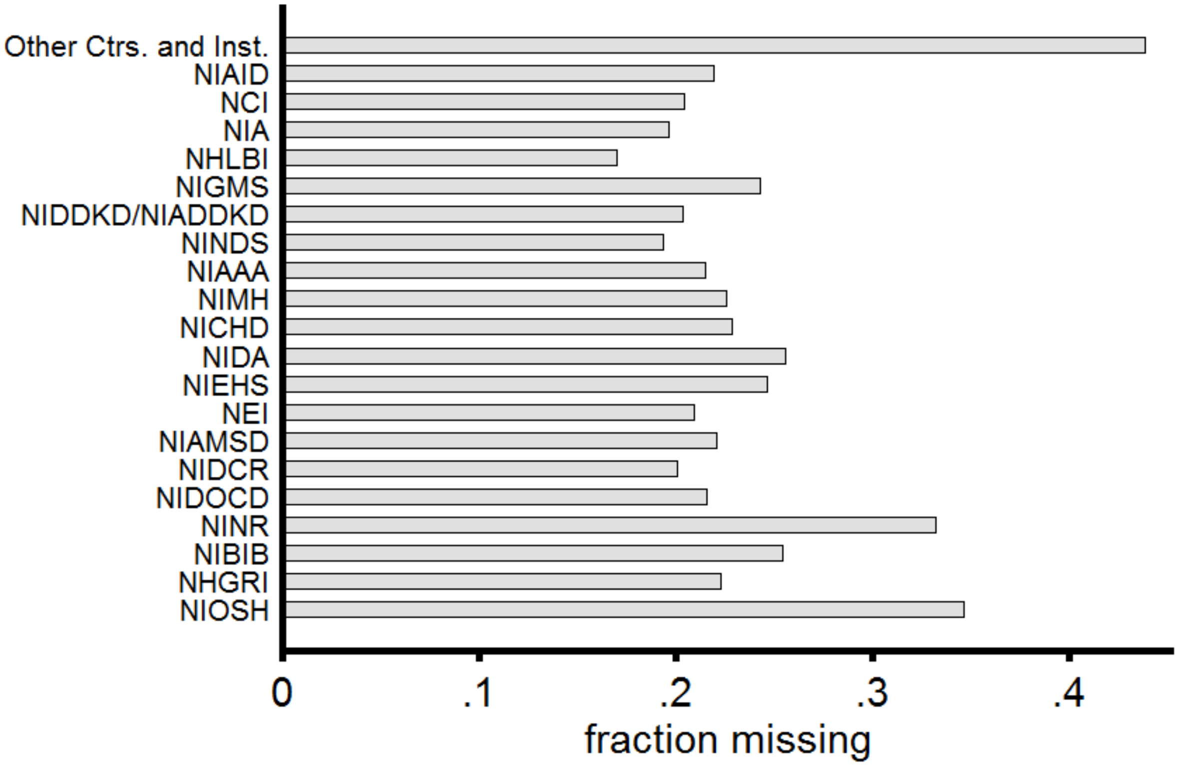
APPENDIX 2

Figure 2.A1. Patterns of application missingness by activity funding code (grant type).



Notes: The proportion of competing applications missing keywords by activity code are shown. The vertical axis shows the first letter of the grant funding type. For information on NIH funding categories, see http://grants.nih.gov/grants/funding/ac_search_results.htm.

Figure 2.A2. Patterns of application missingness by administering NIH institute.



Notes: The proportion of competing applications missing keywords by NIH administering center or institute are shown. The vertical axis shows the major NIH institute that administered each grant. For information on NIH center and institute abbreviations, see http://www.nih.gov/icd/.

APPENDIX 3

Here I reanalyze the association between interdisciplinary dissertation committees and the novelty of the dissertation by operationalizing novelty on the basis of keywords listed by the author of each dissertation rather than high term frequency – inverse document frequency words derived from the abstracts of each dissertation. ProQuest offers the following description of keywords in their data base: "Index terms are keywords in the Identifier/keyword field assigned by the author or ProQuest. You can run a search for any keyword. Index terms in this field do not conform to any controlled vocabulary. When an author submits their dissertation or thesis to ProQuest, they can optionally assign up to six keywords to describe their graduate work. ProQuest may also assign index terms to improve discoverability" (http://proquest.libguides.com/c.php?g=86988&p=560575). For instance, one author might list "Social Sciences, Computer-Mediated Communication, Electronic Markets, Visualization, Finance" while another might list "Health and Environmental Sciences, Biological Sciences, HPV Concordance, Sexual Partners"[12]; these are actual examples of keywords used in the data. I focus on keywords because they are an intuitive concept that is more analytically tractable than looking at dissertation titles and abstracts.

Table 3.A1 contains the same results as Table 3.8, but with novelty defined as keyword combinations rather than abstract term combinations. As can be seen, the results are nearly identical, with the exception that the strong negative effect of committee members from Arts and Humanities fails to replicate. An additional observation is that the r^2s of these models are substantially lower.

[12] I parse each keyword list at the commas, which would, for example, record five keywords for the first author and four for the second; keywords in this operationalization are sometimes key phrases.

Table 3.A1. Predicting core and tail novelty in keyword combinations, by type and area of interdisciplinary members.

	Core novelty			
	(1)	**(2)**	**(3)**	**(4)**
Members	-0.047***	-0.095***	-0.096***	-0.098***
	(0.012)	(0.012)	(0.012)	(0.012)
Interdisciplinary		0.213***	0.114***	0.109***
		(0.012)	(0.016)	(0.016)
Cross-area			0.176***	
			(0.019)	
From:				
Arc				-0.368*
				(0.177)
A&H				0.289***
				(0.052)
Bus				-0.283***
				(0.070)
Edu				0.327***
				(0.057)
Eng				0.075*
				(0.035)
Law				-0.251
				(0.282)
LS				0.312***
				(0.031)
HSM				0.320***
				(0.045)
PSM				0.040
				(0.029)
SBS				0.256***
				(0.033)
Constant	-7.855***	-7.784***	-7.783***	-7.784***
	(0.080)	(0.080)	(0.080)	(0.080)
	61,936	61,936	61,936	61,936
Observations	0.061	0.066	0.067	0.069
R-squared	-0.047***	-0.095***	-0.096***	-0.098***

See notes to Table 3.10.

Table 3.A1 continued.

	Tail novelty			
	(5)	**(6)**	**(7)**	**(8)**
Members	0.026***	0.003	0.003	0.002
	(0.005)	(0.005)	(0.005)	(0.005)
Interdisciplinary		0.098***	0.007	0.005
		(0.005)	(0.007)	(0.007)
Cross-area			0.162***	
			(0.008)	
From:				
Arc				0.092
				(0.075)
A&H				0.041
				(0.022)
Bus				0.095**
				(0.030)
Edu				0.228***
				(0.024)
Eng				0.125***
				(0.015)
Law				-0.075
				(0.120)
LS				0.218***
				(0.013)
HSM				0.177***
				(0.019)
PSM				0.083***
				(0.012)
SBS				0.273***
				(0.014)
Constant	-4.197***	-4.164***	-4.163***	-4.144***
	(0.034)	(0.034)	(0.034)	(0.034)
	61,936	61,936	61,936	61,936
Observations	0.027	0.033	0.039	0.042
R-squared	0.026***	0.003	0.003	0.002

Figure 3.A1. Example of distinction between fields, disciplines, and areas of study.