COMPETITORS AND COLLABORATORS: EXPLORING INTER-UNIVERSITY EFFECTS IN THE ACADEMIC DISCIPLINE OF BIOMEDICAL ENGINEERING

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A dissertation submitted to the faculty at the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Public Policy in the School of Arts and Sciences.

Chapel Hill
2023

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ABSTRACT

Allison S. Lowe Reed: Competitors and Collaborators: Exploring Inter-University Effects
in the Academic Discipline of Biomedical Engineering
(Under the direction of Maryann P. Feldman)

The interaction of proximate research universities is a multifaceted and increasingly relevant phenomenon in today's higher education landscape. The three essays herein add to science policy and innovation literature by exploring the challenges, opportunities, and expectations that arise when multiple universities operate in a region. The first essay identifies significant capacity, reputation, and proximity characteristics that increase the likelihood of having an accredited biomedical engineering program. The second essay argues that inter-university curricular collaboration positively affects research quality due to an increase in the number of patent citations tied to joint biomedical engineering programs. The third essay uses qualitative data to explain that the process of research orchestration involves more than simple transaction cost considerations and may lead to inter-university partnerships.

Motivating the study of inter-university effects by using the relatively new academic field of biomedical engineering is appropriate due to the dynamic nature of the highly technical, interdisciplinary field, in which accumulated knowledge complements access to physical facilities. This research sheds light on the mechanisms that drive collaborative initiatives, foster competition, and influence the quality of higher education research. It contributes to the ongoing discourse on the evolving nature of higher education and its role in shaping the knowledge-driven societies of the future by offering valuable perspectives for policymakers, institutional leaders, scholars, and all those interested in the complex interactions of universities operating within an ecosystem.

ACKNOWLEDGEMENTS

I extend special thanks to Maryann Feldman, my committee chair, for her exceptional leadership and guidance throughout this journey. It has been an honor to work alongside her, and her mentorship has been instrumental in steering my efforts toward success. I am deeply appreciative of the time, expertise, and commitment she has generously devoted to my academic journey. Dr. Feldman played a crucial role in shaping my dissertation, and I am grateful for her continued support and encouragement.

Additionally, I would like to express my sincere gratitude to Dr. Lee Craig, Dr. Jeremy Moulton, Dr. Alex Graddy-Reed, and Dr. Abhi Ghosh Moulick for their invaluable contributions as committee members. Their guidance and thoughtful insights have played a pivotal role in shaping and enriching my research. I am truly fortunate to have had the opportunity to work alongside such dedicated and knowledgeable individuals. Thank you for your unwavering support and commitment to our shared goals.

Finally, my heartfelt appreciation goes to my family for their steadfast patience and support throughout my time in graduate school. Their understanding, encouragement, and resilience have been a constant source of strength. Their sacrifices and belief in me have made my success possible, and I am grateful for the love and stability they have provided.

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1.1 Introduction

The higher education marketplace is increasingly competitive as public resources become scarcer and universities are encouraged to compete for funding and top-notch faculty and students. At the same time, collaboration between universities with complementary strengths may be the key to unlocking more social value in regions that develop unique patterns of social organization connected to frequent contact between researchers (Casper, 2013). The dearth of research regarding interactions between proximate universities might lead one to believe that they merely coexist. Evidence herein shows this is far from the truth.

Universities are prominent in economic development efforts (Nager, Lowe Reed, & Langford, 2019). Academic research in diverse fields examines universities' history, role, and effects on respective areas of interest. Recent science and technology policy literature examines how universities foster technological innovation and the development of policies that support knowledge creation, while economic development policy literature focuses on how knowledge spillover and the creation of human capital foster entrepreneurship and supplement economic growth in an innovative ecosystem (Bloch & Sørensen, 2015; Kantor & Whaley, 2014). A fundamental unaddressed question concerns the effects that multiple universities collaborating or competing have on one another and the surrounding region. This research seeks to understand the implications of university interaction.

Examining these inter-university effects is timely. As research becomes more complex and interdisciplinary, universities will likely collaborate more on an organizational level, trading facilities and stores of knowledge, complementing each other's strengths and adding value to previously discovered knowledge by translating basic scientific discoveries for practical uses. New, highly technical, interdisciplinary fields similar to biomedical engineering will likely develop as researchers push their disciplines' boundaries. With scarce public resources and changing demographics, university leaders acknowledge that collaborating for mutual benefit may be a good path forward.

This chapter serves to elucidate the significance of inter-university research and the alignment of each essay with the overall objectives. It begins by furnishing an introductory perspective on biomedical engineering, the motivating field for each of the three essays, outlining its suitability for addressing the research problem. Next, a science policy and innovation literature review aids in the definition of research goals by highlighting what is well-established in policy literature surrounding universities and what has yet to be explored thoroughly. Finally, the current research aims and significance are briefly discussed, followed by future research paths.

1.2 Overview of Biomedical Engineering

The academic field of biomedical engineering is the ideal context for studying inter-university collaboration and competition. It is highly technical and interdisciplinary, with basic and translational research areas requiring a store of specialized knowledge and physical facilities that can be shared in a complementary fashion. At the same time, the knowledge, processes, and devices created in academic laboratories are highly commercializable, thereby creating competition between researchers.

In Nebeker's (2001) comprehensive account of the establishment of biomedical engineering in the United States, the field is said to encompass the application of engineering principles and methodologies that address challenges within biology and medicine. The multidisciplinary field of biomedical engineering, often abbreviated as BME, effectively harnesses the expertise of professionals spanning diverse domains, including biochemistry, cell biology, immunology, materials science, and surgery, as well as many engineering disciplines including but not limited to aerospace, mechanical, biomolecular, chemical, and electrical (Nerem, 1997). In the broadest context, BME encompasses an array of applications, from developing artificial organs and prosthetic limbs to creating sophisticated imaging instrumentation. It also extends to the design and delivery of pharmaceuticals and medical therapies, the groundbreaking domain of tissue engineering, the development of biological substitutes, and the creation of new laboratory techniques for future discovery (Bronzino, 1999).

The origins of engineering in medicine began in the mid-twentieth century, but a pivotal transformation occurred in 1968 with the creation of the Biomedical Engineering Society. So, while the initial milestones in biomedical engineering date back to the 1950s, marked by the advent of cell cultures and the unraveling of the double helix structure of DNA, the first accredited academic programs dedicated explicitly to biomedical engineering emerged in the early 1970s. Universities with robust medical research programs made significant contributions by synergizing efforts with interested engineering faculty. Additionally, agricultural engineering schools and institutions possessing substantial engineering programs but lacking medical schools were early entrants into the burgeoning field of biomedical engineering (Nerem, 1997). Numerous pioneering developments in BME have been rendered obsolete in contemporary times, owing to the relentless progression of the field.

Presently, the conspicuous facets of BME instrumentation and research predominantly revolve around three pivotal domains, as expounded by Griffith and Grodzinsky (2001): diagnostics, therapeutics, and surgery and rehabilitation. Diagnostics encompasses a spectrum of activities centering on imaging, monitoring, and the development of specialized instruments for medical diagnosis. Therapeutics encompasses a multifaceted arena; this includes sensory technologies, cardiovascular interventions, respiratory advancements, tissue regeneration, tissue engineering, biotechnology, and innovations in biomaterials. Surgery and Rehabilitation encompasses both the creation of advanced surgical devices and the refinement of medical procedures related to surgery and postoperative rehabilitation. The complexity and breadth of these topics necessitate a focused approach. It is, therefore, not surprising that most academic departments specializing in biomedical engineering tend to concentrate their research efforts in select areas within this expansive field.

1.3 Theoretical Foundations

Science and Technology Policy literature, including research on ecosystems and agglomerations, economic geography, technology transfer, and research policy, has established that investments in academic research help shape the future capacity of a region as new knowledge and social capital built through university-industry collaboration are disseminated throughout a region (Kantor & Whalley, 2014).

Academic research is essential because the cost of learning by failure is too high for most (Veysey, 1965). The old linear knowledge innovation model in which academic science leads to innovation that later brings commercial success to private industry has evolved to an interactive model where industry, academia, and government create regional innovation systems (Bloch & Sørensen, 2015; Etzkowitz, 1998). In fact, knowledge creation leading to innovation is the expectation of academic research today (Bercovitz & Feldmann, 2006). Often held up as examples of economic development and anchored by strong research universities, both Silicon Valley and Route 128 were built on regional and institutional strengths (Dietz, 2000).

Notably, influential research studies such as Etzkowitz's (1998) "Triple Helix" model and "R&D Spillovers and the Geography of Innovation" by Audretsch and Feldman (1996) posit that universities are pivotal in innovative regional ecosystems. They generate and disseminate novel knowledge, facilitate workforce development, and enhance aggregate levels of human capital in a region. We expect the amplification of knowledge spillover near patent citation-prone industries and the alignment of research interests between universities and industries (Audretsch & Feldman, 1996; Kantor & Whaley, 2014; Henderson, 2007). University spillovers are most intense in the surrounding region, where local industry might hire graduates and utilize university patents that make use of academic research to a greater extent (Drucker, 2016). Programs and initiatives that increase the capacity for research that is complementary to local industry have the greatest chance of maximizing the social benefit in a region (Muscio, Quaglione, & Vallanti, 2012).

Theories of academic capitalism, as explored by Slaughter and Rhodes (2004), investigate the motivations and outcomes of academic entrepreneurs who seek to commercialize knowledge. Common elements of university-industry interactions include sponsored research, intellectual property licensing, labor supply, and the emergence of new startup companies. Universities significantly contribute to the local economy through direct employment, income generation, the cultivation of human capital, technological advancements, and knowledge transfer to industry (McCann & Ortega-Arguiles, 2019). Moreover, regions with universities have improved future growth potential as expenditures for all types of academic research (basic, applied, and development) continue to increase (Valero, 2019; Thursby & Thursby, 2011).

Suppose we accept Valero's (2019) argument that the establishment of a university is positively correlated with future economic growth. A question that follows might be, what are the specific dynamics of this correlation in relation to different types and quantities of universities? When researchers examine how universities are part of an innovative ecosystem, the effect they have on one another and how that translates to the economy and the stock of knowledge in the region is usually not included. Current policy literature rarely explores the impact multiple universities in an area have on one another and the region, nor does it include differentiating characteristics of universities. Instead, universities are often treated as relatively homogeneous organizations (Uyara, 2010). We don't know how multiple regional universities should change the expectations and importance of universities in the Triple Helix. Nor can we identify the marginal effects of an additional university in a regional economy. Is the additional university a substitute or a complement that changes the quantity or quality of spillover in a region? Further investigation of inter-university collaboration and competition is required to answer these questions.

Admittedly, exploring the dynamic relationships between research universities presents a challenge due to their complex nature. The inherent endogeneity of universities, industry, and regional development further complicates the pursuit of significant findings. This research focuses on the academic field of biomedical engineering to facilitate the establishment of collaborative partnerships or competitive dynamics among universities and, subsequently, to discern any consequential impacts stemming from these interactions.

1.4 Overview of the Dissertation

Each essay included in this dissertation contributes to our understanding of inter-university interaction. The findings have implications for economic development, research policy, higher education administration, and science and technology policy. *Table 1* summarizes the dissertation chapters that follow by listing the title, research question, model and data, and main results. The chapters exhibit thematic coherence, although they draw from distinct bodies of literature. Chapter Two, *University Signaling: Factors Leading to Accreditation in a New Scientific Field*, incorporates literature on signaling strategy and the emergence of academic disciplines to add context to the interpretation of BME program accreditation. Chapter Three, *Does Inter-university Curricular Collaboration Produce Quality Research Results?* includes insights from research on collaboration and higher education policy to set the stage for comparing the quality of university research in BME. Chapter Four, *Inter-university Partnerships: The Intrapreneur's Path in a University's Make-Buy-Partner Process*, leans heavily on entrepreneurship literature to create a framework to consider qualitative data surrounding the expansion of BME programs in four case studies. Each paper also draws on different data sources and methodologies, but all motivate the research question within the context of biomedical engineering academic programs. Overall results show that university interaction, whether competitive or collaborative, is a significant consideration for researchers. Avenues for future research exploring university interactions are extensive and poised to gain significance as faculty become increasingly relied upon to address progressively intricate interdisciplinary inquiries. At the same time, the marketplace for higher education continues to evolve.

The following chapters will explore the impact universities have on one another, collaboratively and competitively, answering three research questions motivated by biomedical engineering: 1. What are the institutional and environmental characteristics of universities that become accredited in biomedical engineering? (Are all significant characteristics a mark of quality?) 2. What is the effect of organization-level curricular collaboration on the quality of academic research in the interdisciplinary field of biomedical engineering as measured by patent citation counts? 3. Are there similarities in inter-university partnerships created to expand access to resources in BME programs?

1.4.1 Chapter Two: University Signaling: Factors Leading to Accreditation in a New Scientific Field

The characteristics of accreditation of higher education programs are widely seen as a mark of quality. While commonalities among accredited universities support this view, competition between closely ranked and geographically proximate universities muddy the signal value. The diffusion of new interdisciplinary academic areas further complicates the interpretation of the signal. This paper looks at the characteristics and interdependent actions of universities that become accredited in the relatively new interdisciplinary academic field of biomedical engineering. The discreet-time event history analysis model employed herein confirms accreditation signals attributes of quality not easily observed by outside parties. Still, there is also a significant geographic bandwagon effect that is not explained by unit or historical variables.

The research findings provide valuable insights for policymakers and university leaders regarding the diffusion and advancement of new scientific fields in academia and the significance of program accreditation as an indicator of quality while adding to the literature on emerging scientific academic fields, signaling strategy, and collaborative ecosystems. Diffusion patterns emerged from universities with well-established reputations and robust academic capacities to institutions of comparatively lesser prestige. Leading institutions also influence geographically proximate universities, elucidating the ways in which knowledge and expertise are disseminated. The results underscore the necessity of considering the characteristics of nearby universities in ecosystem research, challenging the notion that they can be disregarded.

1.4.2 Chapter Three: Does Inter-university Curricular Collaboration Produce Quality Research Results?

The handful of accreditations awarded to joint BME programs that cross university boundaries stood out within the competition to achieve legitimacy in the new academic field of biomedical engineering. Chapter three builds on the knowledge that collaboration plays a pivotal role in unlocking new insights and expanding the capacity for innovation (Bercovitz & Feldman, 2011; Boland et al., 2017; Levinthal & March, 1993). Individual-level collaboration is common among academic researchers, but organizational-level collaboration between two universities is more difficult to define and less studied. Evaluating collaborative strategies that pool human capital and university facilities to increase innovation and new knowledge is integral for policymakers in the current knowledge-based economy (Bozeman, Fay, & Slade, 2013). This chapter explores the effect of university-level collaboration on the quality of academic research in the interdisciplinary field of biomedical engineering using patent citation counts as established in the literature (Hourihan, 2020).

Two types of inter-university collaboration, research and curricular, are analyzed using patent data. Patents with two or more university assignees or multiple inventors in separate locations indicate research collaboration, while joint programs, degrees, or departments denote curricular collaboration. Using cited patents as evidence of innovation, a truncated negative binomial model identifies the effect research and curricular collaboration have on the quality of university patents. Results show no significant effect from research collaboration but a 40% increase in expected patent citations for patents created at universities with curricular collaboration. This result is similar, though smaller, to the increase in expected citations for patents with university-industry collaboration and points to the importance of more research surrounding the motivation and effects of inter-university collaboration as a key to innovation.

1.4.3 Chapter Four: Inter-university Partnerships: The Intrapreneur's Path in a University's Make-Buy-Partner Process

The fourth chapter of the dissertation explores the endeavors of four prominent research universities as they strategically sought to enhance access to medical facilities, driven by their ambitions to expand both research and development (R&D) initiatives and curriculum offerings. The findings underscore a critical insight: the approach research universities adopt to augment access to facilities and knowledge, especially in highly technical and interdisciplinary fields like biomedical engineering, is far from a straightforward "make-or-buy" decision. Instead, it unfolds as a multifaceted process involving elements beyond mere transactional considerations. Within this process, inter-university collaborations emerge as a viable avenue once the aspiration for expansion takes root and resource requirements become apparent. In this complex landscape, intrapreneurs—individual research faculty members who venture beyond their conventional roles—play a pivotal role in nurturing research capabilities through inter-university partnerships. Leadership support and institutions dedicated to continually reducing collaboration costs across university boundaries emerge as critical factors for success.

Qualitative observations lead to a structured framework for assessing the growth trajectories of interdisciplinary academic programs and provide valuable guidance for policymakers and researchers interested in dynamic areas of translational research. Furthermore, university leaders exploring future inter-university collaborations will find this framework particularly pertinent and insightful.

1.5 Future Research

As research inquiries grow in complexity and the quest for complementary knowledge transcends the confines of individual campuses, the significance of investigating university interactions is poised to increase. Biomedical engineering exemplifies the trend toward combining specialized knowledge in innovative, interdisciplinary ways. New fields like this are likely to develop. The imperative of making the most of complementary resources from neighboring universities, particularly in the face of resource constraints, offers mutual benefits to the collaborating organizations. This introductory chapter lays the foundation for a journey of exploration and inquiry. Within each essay, examples of potential extensions in future research endeavors are provided at the end of each chapter. It is my aspiration that larger research projects within this domain will dive into the nature of universities as substitutes or complements to one another and the partnerships surrounding interdisciplinary centers and research facilities on university campuses. These avenues promise to yield valuable insights into the dynamics of inter-university collaborations, thereby advancing our understanding of this crucial facet of the academic landscape.

Table 1.1

Overview of Dissertation

Competitors and Collaborators: Exploring Inter-University Effects in the Academic Discipline of Biomedical Engineering			
Chapter Title	**Research Question**	**Data & Model**	**Results**
University Signaling: Factors Leading to Accreditation in a New Scientific Field	What are the institutional and environmental characteristics of universities that become accredited in biomedical engineering? (Are all significant characteristics a mark of quality?)	Cox proportional hazards model (Discrete event history analysis) Novel data set sourced from IPEDS and ABET with observations on 485 universities at risk of program accreditation in biomedical engineering from 1970-2020.	The value of accreditation as a signal of quality is reduced due to the significant effect of proximity variables. Results show that the probability of creating an accredited BME program is correlated with proximate university accreditation, in addition to other university fixed effects representing capacity and reputation.
Does Inter-University Curricular Collaboration Produce Quality Research Results?	What is the effect of organization-level curricular collaboration on the quality of academic research in the interdisciplinary field of biomedical engineering as measured by patent citation counts?	Truncated negative binomial regression identifies the effect research and curricular collaboration have on the quality of university patents 990 BME university-owned patents that have at least one patent citation. Collected using keyword search and CPC code from USPTO. (5 CPC codes a61B, a61f, a61K, a61m, a61N)	Inter-university curricular collaboration in BME leads to higher quality research; a 47.8% increase in expected patent citations. Results could be extended to other highly technical interdisciplinary academic fields in the future.
Inter-University Partnerships: The Intrapreneur's Path in a University's Make-Buy-Partner Resource Orchestration Process	Are there similarities in the inter-university partnerships created to expand BME programs?	Multiple case study Qualitative data gathered from 17 interviews, internal documents, and published information	Identification of common make-buy-partner process with key role of intrapreneur identified in creation of inter-university partnerships

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CHAPTER 2: IS ACADEMIC ACCREDITATION A RELIABLE SIGNAL OF QUALITY?

2.1 Introduction

Signals are visible actions designed to communicate unobservable but alterable attributes (Spence, 2002). Incentives to signal may be different for each organization; however, because they are costly, signals often provide valuable information regarding quality (Spence, 2002). High-quality producers wishing to differentiate themselves from low-quality competitors in the marketplace may do so by offering warranties or obtaining endorsements and certifications that serve to lessen information asymmetries and generate competitive advantage (Terlaak & King, 2006). For these signals to be useful in the marketplace, each should accurately convey the truth.

In the higher education marketplace, universities obtain funding from varied sources and compete for resources on many levels. A few top universities with excellent reputations may have no need to signal their quality, but the competitive nature of the higher education marketplace likely incentivizes many universities to do so for reasons directly related to funding and the accumulation of human capital. While some universities focus on recruiting students to enhance funding tied to enrollment, others may focus on recruitment of top research faculty and graduate students to enhance the prospect of future grant funding from federal and industry sources.

In the traditional economic model of a costly signal, a separating equilibrium exists when only high-quality organizations can rationally signal they are high-quality by obtaining certification or accreditation. If a university with demonstrated capacity is more likely to signal quality by becoming accredited when similarly ranked institutions are also accredited, that leads us to believe that a separating equilibrium exists, and the signal is clearly valuable in the marketplace. However, the signal loses value when there is no clear distinction based on quality. To clarify, when accounting for various institutional, environmental, and historical variables known to enhance the probability of accreditation for a high-quality university program, the presence of a statistically significant bandwagon effect changes the informational value of the accreditation signal. This research aims to discern the influence that nearby universities exert on one another's choices to enter a relatively new academic field and pursue accreditation, utilizing accreditation as a quality indicator for prospective students, faculty members, peers, and funding organizations.

Competitive research universities are obligated to obtain institutional accreditation from a regional accreditation board to qualify for federal tuition subsidies and research grants, forming an essential prerequisite. However, beyond institutional accreditation, universities have the discretion to pursue additional accreditation for programs from specialized private agencies. This pursuit of secondary accreditation serves as a calculated choice, driven by the desire to enhance their perceived image among various stakeholders, including prospective faculty members and students, grant providers, political constituencies, alumni supporters, and potential research collaborators, as elucidated by Arielly, Bracha, and Meier (2009). In the context of academic engineering programs, the Accreditation Board for Engineering and Technology (commonly referred to as ABET) stands as the preeminent and widely recognized accrediting body for engineering programs (Enroll Education LLC, 2023).

In addition to accreditation, universities employ various strategies to effectively distinguish themselves in a fiercely competitive landscape. These strategies encompass endeavors such as credible expansion into emerging academic domains and the establishment of robust academic research initiatives. Academic research literature underscores the positive correlation between an institution's reputation and its capacity to attract a larger, higher-caliber applicant pool. Within this framework, a favorable reputation, denoting an organization's overall attractiveness relative to its peers, significantly augments the efficacy of recruitment efforts (Turban & Cable, 2003).

For large research universities increasingly reliant on grant funding as a significant revenue source, the accumulation of human capital in the form of faculty and graduate students plays a pivotal role in securing grants. The track record of previous research outcomes also influences these grants. This connection between research outcomes and grant funding underscores the importance of reputation-enhancing signals for universities. Additionally, universities aiming to maximize tuition income can benefit from cultivating a strong reputation, as individuals derive greater utility when associated with organizations of higher reputation (Turban & Cable, 2003; Arielly et al., 2009).

In the following sections of this paper, I will discuss signaling and biomedical engineering accreditation requirements in detail. The data and model are specified next, followed by a presentation and discussion of model results. In the final section, a summary and conclusion are provided. Results from the model suggest accreditation is a weak signal of quality due to the significant effect of geographically proximate universities on the likelihood that a university engineering program is accredited.

2.2 Accreditation of Biomedical Engineering Programs

Across the nation, many biomedical entities exist, encompassing centers, departments, research laboratories, and academic programs within universities, offering degrees ranging from bachelor's to Ph.D. levels. Notably, the landscape of biomedical engineering (BME) departments exhibits diversity, with some operating independently while others are integrated within larger engineering departments or medical schools. The present study delves into an examination of the institutional and environmental attributes influencing the expansion and accreditation processes of BME programs, as well as an exploration of the significance of accreditation as a quality-indicating signal in this context.

Signaling literature tells us that a substantial cost must be associated with a valuable signal, and visibility is important when extrinsic motivators are weak (Spence, 2002; Arielly, Bracha and Meier, 2009). Accreditation of an engineering program is costly and commonly recognized as a signal of sustainable quality for an academic engineering program. Universities often feature their ABET certification prominently on marketing materials for engineering programs. Though individual programs are certified, universities may merely state they are ABET certified, as if it is a university-wide seal of approval for engineering. This seems especially true for marketing aimed at students who do not know the difference. While some universities in this sample boast 24 accredited ABET programs, others have only one (or none). The imperfect information regarding the meaning of an ABET certification further muddies the value of the signal. It may be that a university does not feel the need to get all quality programs certified.

The Engineering Accreditation Commission (EAC) of the Accreditation Board for Engineering and Technology (ABET) accredits engineering programs with separate general standards for baccalaureate-level programs and master's level programs and content area-specific criteria. Each program must have conferred degrees before becoming accredited. Faculty must have sufficient competencies, facilities must be adequate, and institutional support must be present to ensure the quality and continuity of the program (ABET, 2022). Becoming accredited is a multi-year endeavor to obtain outside verification of expertise and longevity. It signifies legitimacy and the presence of a substantial reservoir of implicit knowledge within the department to students, industry stakeholders, prospective faculty members, and grant providers.

The first year ABET issued accreditations for engineering programs was 1936. At that time, the conventional engineering fields of civil, mechanical, geological, and electrical engineering were already well-established in colleges of engineering. Several additional new engineering disciplines, such as chemical, nuclear, architectural, and computer engineering, followed in later years. *Table 1* lists the main engineering programs accredited by ABET. The span of accreditation years identifies the initial and final years during which a specific engineering program received accreditation. The mean accreditation year provides insight into the period when demand for the particular engineering program reached its highest level of popularity. Biomedical engineering (BME) is the newest engineering discipline to be widely offered by research universities. Only computer engineering grew faster as a discipline. The first year of accreditation for a biomedical engineering program, 1972, is later than all other engineering programs in the chart. Interestingly, some universities claim their departments were in existence for many years prior to this date. The mean accreditation year, 2004, is six years later than the next closest program means. Around this time, many universities were applying for accreditation of their BME program, regardless of age, due to funding incentives and competition for faculty and students.

Accredited BME programs must "apply the interdisciplinary principles of engineering, biology, human physiology, chemistry, physics, calculus, and statistics to solve engineering problems associated with the interaction between living and non-living systems." (ABET, 2022) Biological and biological systems engineering programs are accredited using different curriculum criteria that focus on engineering, biology, and chemistry and do not specifically mention human physiology and statistics. Several universities with longstanding accreditations in biological or biological systems engineering programs also have accredited BME programs, but some do not. These schools often claim to be pioneers in biomedical engineering research yet have recent BME program accreditation dates. Clemson University serves as an illustrative case. While the first graduate of their bioengineering program completed their studies in 1963, the program itself did not obtain accreditation until 2009. This shows that adding accreditation to a BME program is a strategic move by research universities and represents more than a mark of quality.

ABET claims accreditation adds value for students and institutions because it "assures confidence that a collegiate program has met standards essential to prepare graduates to enter critical STEM fields in the global workforce" (ABET, 2022). Students are told ABET accreditation enhances employment opportunities, for which ABET certification is often a requirement. Institutions are advised accreditation yields “data and insight” that can be used to produce a better student experience. The website also says, “ABET accreditation tells your prospective students, peers, and the professions you serve that your program has received international recognition of its quality and promotes *best practices* in education” (ABET, 2022). The organization also encourages employers to require job applicants to graduate from an ABET-accredited program as a hiring requirement.

ABET certification fees average $10,000 for an initial program certification. For universities with no existing program certifications, a readiness review is also required before the accreditation assessment begins, which increases the explicit cost of the first review. The review itself lasts only two days, but the time commitment is much greater. All ABET certifications from the EAC require (1) graduating students, (2) published program education criteria, (3) documented student outcomes, (4) a documented process for assessment, (5) curriculum requirements appropriate for subject areas, (6) sufficient competent faculty to cover all curricular areas of the program, (7) facilities, and (8) institutional support and leadership including financial and administrative support. Requirements specific to BME program evaluation include a curriculum that provides for principles of engineering, biology, human physiology, chemistry, calculus-based physics, mathematics, and statistics training where students “solve bio/bioengineering problems associated with the interactions between living and non-living systems” (ABET, 2022).

In addition to monetary expenses, the time required to develop and organize the needed material for assessment necessitates that faculty be removed from teaching and research responsibilities. It is the total opportunity cost of certification that must be considered when making the decision to become ABET certified. While the explicit cost may be too high for universities without faculty expertise and adequate facilities to complete the requirements, the implicit cost may be too high to bear for some highly productive research programs. The decision of certain top-tier programs with strong academic standing to forgo accreditation introduces complexity to the straightforward theoretical signaling model, yet it does not invalidate the paradigm. Much like exceptional, highly productive students who possess the capability to complete a university degree but opt not to due to the substantial opportunity cost associated with foregone potential earnings, prestigious universities endowed with productive research programs and well-established reputations may make a rational choice to disregard multiple program accreditations. This choice stems from a cost-benefit analysis where the anticipated benefits do not outweigh the perceived loss in productivity.

The cost of accreditation is incurred by universities that want to signal their ability and intent to contribute new knowledge in an academic field while also showing they have the intrinsic knowledge needed to succeed. For these reasons, the diffusion of accreditation of BME programs is a significant milestone to track in the development of the field.

2.3 DATA AND DESCRIPTIVE STATISTICS

The data for this analysis consists of historical and unit-specific variables related to 485 universities in the United States (excluding territories) deemed to be at risk of becoming accredited in BME because each has either an existing medical school or at least one ABET accredited engineering program.[1] These parameters were chosen because there is no accredited biomedical engineering program without at least one of these characteristics in the United States. In the year 2020, among the 124 universities hosting accredited BME programs, 21 of these programs achieved accreditation prior to 1990. The majority of accredited programs, however, were established within the time frame spanning from 1995 to 2018. BME is now the 7th most popular type of engineering program as determined by the

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[1] The list of universities with at least one accredited engineering program was obtained from ABET.org. Universities with only one accredited Engineering Tech program were not included as at-risk. Engineering tech programs focus on implementation and application. They do not require courses in theory or high-level mathematics. The list of universities with a medical school was obtained from Motivate M.D., (https://www.motivatemd.com/list-of-medical-schools/).

number of accredited programs. Only civil, chemical, mechanical, electrical, general, and computer engineering disciplines have more accredited programs.

The independent variables utilized as control parameters in the analysis, which encompass both constants and variables that change over time, can be classified into three discernible categories predicated on their relevance to universities. An independent variable may pertain to a university's reputation if it influences perceptions held by various stakeholders. Alternatively, it may be associated with a university's capacity to facilitate education and engage in research if it reflects the accumulation of human capital, physical resources, or specialized knowledge. Finally, an independent variable falls into the category of proximity-related variables if it pertains to competitive dynamics or patterns of agglomeration within the geographic vicinity of the university. According to signaling theory, both reputation and capacity variables should be significant in defining the likelihood that a university signals quality by seeking accreditation for a new engineering program in a given year. If proximity variables are statistically significant predictors of accreditation, this broadens the interpretation of accreditation as a signal. Additionally, a significant proximity covariable means future research on agglomeration and ecosystems would do well to include proximate university characteristics in their analysis. The significance of proximity variables points to an overestimation of the marginal effect that local industry may have in models that attempt to measure university-industry relationships without this control.

While controversial, ranking lists produced by a variety of sources are the most obvious mark of reputation for a university. Consequentially, it is likely that universities use rankings to help determine their peers and establish strategy. In their analysis of the impact of rankings on higher education, Hazelkorn (2018) notes there are over 150 different national and specialist rankings of universities in the United States and almost 30 global ranking systems for institutions competing internationally. Each ranking system has a different evaluation criteria and audience that includes students, parents, governments, employers, investors, collaborators, business partners, and the general public, as well as media outlets. Based largely on what can be measured rather than what is necessarily relevant and important to the university or surrounding regions, rankings weigh heavily on university decision-making because they signal excellence to outsiders and help determine resource allocation, including faculty, students, and funding (Lepori, Geuna, & Mira, 2019; Hazelkorn, 2018). Though rankings are widely used as a measure of quality internationally, it has been argued they actually measure university wealth, not excellence (Johnes, 2018). They also create incentives for government interference because states benefit from having top-rated universities within their borders (Hazelkorn, 2018). The rating systems with open ranking criteria are the most easily manipulated but also the most useful to stakeholders. Arguments for limiting the use of rankings have not advanced because organizations that originate rankings are diverse, ranging from universities to media conglomerates, and rankings are seen as useful in gathering comparable quantitative data and information in a complicated marketplace.

It is common to see billboards along major highways on which universities tout their latest rank on some undisclosed list. A university's standing in influential ratings affects the flow of research dollars, accumulation of human capital, and student migration to a region. These rankings are based on peer reputation, as well as measurable attributes that can be manipulated. One of the best-known ranking lists is US News and World Report (US News, 2022). According to prepscholar.com, The US News ranking list is the "gold standard" because it is the most well-known and highly referenced (Berkman, 2022). US News rankings, which began in 1983, dominate undergraduate rankings in the United States (Diver, 2022).

A time series dataset originating from the US News university rankings served as the basis for calculating an average rating for each university. It is noteworthy that the size of the ranking list has expanded over time in tandem with its increasing popularity. To guarantee the presence of a rating for every university within the timeframe spanning from 1983 to 2022, an approach was employed where the most recently available ranking was used to fill in missing data for universities that did not receive a ranking in a prior year. For universities rated only in recent years, the average rating is biased towards the relatively larger pool this is ranked in more recent years. It is common for universities to be tied in the published rating, so this is not a problem in the data used herein. *Figure 1* visually presents the distribution of changes in ratings observed between 1983 and 2022. Some of the changes in discrete annual ratings and the expansion of the distance between each university's best and worst ratings can be explained by the expansion of the number of universities rated, as well as the changing metric used to calculate scores. The first US News university ranking list in 1983 included ten schools. It expanded to 25 schools in 1991 and 50 schools in 1996. There are currently over 200 ranked universities on the list. Of the 122 ranked at-risk universities included in the data set, fifty percent had discrete changes from best to worst rankings of 20 or less from 1983-2022. Eighty-two percent of ranked universities had discrete changes in rank of 40 places or less, representing an average annual change of one place or less in the forty-year period. Universities with more significant swings from best to worst are primarily in the lower two tiers of universities grouped by the average rating for the period. Only the University of Illinois at Urbana-Champaign fell from a "best" rank below 35 by more than 40 spaces in the period considered; it was ranked eighth in 1983 but never went above the rank of 20 in subsequent years, ending with an average rank of 32.65. No university experienced a sudden shift in its ranking that equates to an average change of two positions each year.

Due to the small number of extreme changes in ranking within the observation period and the absence of large year-to-year fluctuations, a university's average ranking provides insights into its peer group. Following this logic, the average rating is utilized as a basis for establishing two distinct cohorts: the aspirant cohort and the current cohort. The aspirant cohort comprises the five universities having average ratings immediately higher than that of the university under consideration. The current cohort includes the five universities with rankings directly lower than the university in question. Universities not ranked during the study period were assigned the five lowest-rated universities as their aspirant cohort. All unrated universities were grouped into their own current cohort. Additionally, the average ranking was used to categorize universities into five distinct reputational tiers: "Top Five," "Super Competitive," "Very Competitive," "Competitive," and "Not Ranked." The reputational tiers provide a lens to visualize changes and typical characteristics of universities of similar status.

While reputation variables give us an idea of how universities compare in the minds of the public, capacity variables control for the knowledge and skills needed to create and sustain a biomedical engineering program. All universities in the sample population have at least one medical school or one accredited engineering program because it is possible that either discipline could spawn a biomedical engineering program due to its interdisciplinary nature. Universities with medical schools were identified using MotivateMD.com (List of Medical Schools, 2022), and universities with accredited engineering programs came from the ABET website (ABET, 2022). A variety of institution-specific variables were collected from the Integrated Postsecondary Education Data System (NCES, 2022).

Funding data available for BME research was gathered for the National Institutes of Health (NIH, 2022) as a way of modeling the annual trend that is constant across all units. Because federal funding to Institutes that commonly fund biomedical engineering research increases annually, it serves as the baseline historical trend for the growth of BME following similar upward trends in student demand and growth of the industry. In addition to federal grant funding, the privately funded Whitaker Foundation was a major funding source for BME programs from 1988 to 2006. The foundation provided multimillion-dollar grants to academic BME departments during this period. A list of grants provided is in Table 2A.

Table 2B shows the increase in annual federal funding as described above. The NIH funding in the model is not meant to include all BME research projects that received federal funding. Rather, it is meant to show the trend in available funding for BME research by tracking the total funding available in three institutes that would be most likely to fund such projects, given their goals and missions. The National Institute of Biomedical Imaging and Bioengineering (NIBIB) was created in 2000 "to transform through engineering the understanding of disease and its prevention, detection, diagnosis and treatment." The

NIBIB budget for research grants has grown from \$100 million to more than \$500 million in twenty years. Biomedical engineering research projects that received funding before the existence of the NIBIB were likely to be funded by two other Institutes, The National Human Genome Research Institute (NHGRI) and the National Institute of General Medical Sciences (NIGMS). NHGRI funds research in bioinformatics and computational biology, among other areas, “to advance the field of genomics and the treatment of specific diseases to improve human health.” It was established in 1989. NIGMS was established in 1962 to support research that "increases understanding of biological processes and lays the foundation for advances in disease diagnosis, treatment, and prevention.” Research in cells and tissues is specifically mentioned. NIGMS also offers leadership in training next-generation scientists and developing research capabilities throughout the U.S., which is certainly relevant to an expanding field like BME.

Predictor variables that measure the university’s capacity to obtain accreditation also include the level of biotech agglomeration and unobserved geographic fixed effects surrounding a university. Economic geography and theories of agglomeration lead us to believe areas with more biotech and biomedical firms would be positively correlated with the strength of an academic research program (Feldman, 1994). Literature has also established that spillover extends sixty miles from a university, so a strong biomedical academic or research program could also affect the surrounding industry in the opposite direction (Drucker, 2016). The total number of firms within a sixty-mile radius and the number of biomedical firms in the same area were collected from the Data Axel database (Data Axel, 2022). Mathematically, the variable *FirmsRatio* is the number of BME firms per 1000 firms within a 60-mile radius of the university in 1997. A single year was chosen to reduce endogeneity; we would expect the firms in an industry and the strength of nearby university programs to be positively correlated within a set period as researchers interact. In 1997, the BME industry was growing but not yet mature. This date is at the beginning of the main wave of BME accreditations. Though only a snapshot, *FirmsRatio* serves as a measure of industry agglomeration surrounding each university and possibly controls for any localized fixed effects that might be linked to academic accreditation.

Regional fixed effects for different areas of the country are represented using multi-state regional divisions established by the U.S. Census Bureau and summarized in *Figure 2.* The U.S. Census Bureau established four regions divided into eight smaller regional divisions: Pacific, Mountain, West North Central, East North Central, West South Central, East South Central, Middle Atlantic, South Atlantic, and New England. The largest regional division by population is the Pacific division. It serves as the base regional division for comparison purposes. The regional divisions with the most at-risk universities are Middle Atlantic and East North Central, both with 77, and South Atlantic, with 76 universities included in the model. The regions with the highest percentages of accreditations among at-risk universities are the Middle Atlantic, New England, and East North Central regional divisions. Two of these regions also have the highest rate of population with at least a bachelor's degree; 39.3% of the population in the Middle Atlantic division and 43.4% in the New England region, compared with 35.6 for the U.S. as a whole. The New England division has the highest percentage of at-risk universities included in the US News ranking list (34.2%). The disparity in the percentage of accreditations between regions supports the significance of proximity variables in the model.

Other unit-specific measures of capacity for each university include the number of accredited engineering programs in a given year, whether the Carnegie classification system categorizes a university as a doctoral university with very high (R1) or high research (R2), and whether a university has both a medical school and an accredited engineering program in a given year. The divisions with the highest percentage of at-risk universities with very high and high research activity include East South Central (60.7%), Mountain (55.6%), and West North Central (50%).

The disparity in accreditations between regional divisions in *Table 3* supports the hypothesis that proximity variables may play a significant role in the decision to seek accreditation. Proximity explanatory variables were calculated using the latitude and longitude of each university in the sample. This final category of independent variables gives us information about the effect of proximate universities on one another. The variable *Nearby* counts the number of universities within a 60-mile radius. The variable *NearbyYr* identifies the first year a proximate university gets BME program accreditation, and another dichotomous variable, *NearbyBME,* turns on in the year when the first proximate university receives accreditation for a BME program.

Table 3 Summarizes university-specific variables grouped by the previously mentioned rating categories. Independent variables are arranged based on their contribution to explaining a university's reputation, its capacity to become accredited, or the effect of proximate universities on the likelihood of accreditation. Just by looking at summary statistics, it is evident that accreditation is most popular for universities in the third highest "Very Competitive" category, where 80% of universities with average ratings between 26 and 75 are accredited. The universities in this group have the highest number of accredited engineering programs (10.24). Most have high or very high research designations (.93) along with endowments of over a billion dollars (.78). This category also has the highest percentage of land grant universities (.37).

Additionally, it is interesting to note the trend in average accreditation dates starting with the super competitive and ending with non-ranked, where each category's average year for BME accreditation is later than the category before. It is this trend that best illustrates the diffusion pattern of BME accreditation according to the reputation of the university.

2.4 Methods

This paper employs a discrete-time event history model to identify significant independent variables, both fixed and time-variant that are correlated with an increased risk of obtaining accreditation for a biomedical engineering program in any year between 1970 and 2020. Event history analysis is a regression technique for performing survival analysis; it is so named because it initially measured time to death. However, it is commonly used to analyze time to event with one event per unit.

The model uses a data set of 485 universities with predictor variables observed from 1970-2020, with between 1 and 51 years of annual observations per university for a total of 22,786 observations. The average observation period is almost 47 years, and there were 124 accreditations in the observation period. Data are right censored; the time of the event is greater than the censoring date for most universities at the end of the observation period. We do not know when universities will reach the event after this date.

The hazard rate for a discrete-time event history analysis model measures the risk of an event occurring within a year in the observation period. It is calculated as the probability of failure divided by the probability of survival (Box-Steffensmeier and Jones, 2004). It assumes the hazard ratio, the probability of a given event, is determined by risk factors represented by continuous or categorical variables, and the effects of different variables on survival are constant over time and additive.

The Cox Proportional Hazard model is the primary model employed in this paper. The output of the Cox Proportional Hazard model is useful in determining risk conditional on time and independent covariable values (Box-Steffensmeier and Jones, 2004). The unit of analysis in the model is a single university with multiple annual observations of predictor variables. The advantage of using the Cox proportional model instead of other survival analysis models is the baseline hazard function is undefined, so the shape of the function is not predetermined. This leads to a better fit when the shape of the function is truly unknown, but it is also less efficient (Abd El Hafeez et al., 2021).

The primary aim of using the Cox Proportional Hazard model is to gain insights into the factors that influence survival outcomes. It operates under the assumption of a consistent baseline hazard that applies uniformly to all units being analyzed. This model is categorized as semi-parametric because it does not require specifying an underlying function, but it does assume a baseline function that remains constant across time for all units (Abd El Hafeez et al., 2021). The definition of this baseline unit is determined by variables that are shared across all units, and it must be estimated post-analysis by smoothing out any discontinuities in the rate of change between distinct time points (Cleves et al., 2008).

In essence, the shape of the baseline hazard function is consistent for all units under examination when covariables remain constant across these units. In this particular model, the annual grant funding available to NIH Institutes that commonly support Biomedical Engineering (BME) research serves as the determining factor for the baseline hazard function. The baseline function increases with time and is positively correlated with the rising popularity of BME research and increased interest from students in the BME curriculum.

Unique hazard functions are distinct for each unit and are influenced by independent covariates specific to each unit. However, the cumulative effects of these covariates remain constant over time. To put it differently, the impact of a nearby university obtaining BME accreditation (or any other covariable) is the same in 1980 as in 2002, indicating that the effect does not vary with time or by university.

The mathematical model for the hazard rate is $h(t) = \text{Baseline } h(t)^{b_1x_1 + b_2x_2 + \dots b_kx_k}$. The hazard rate at any time t is proportional to the baseline hazard rate and dependent on unique characteristics (x_1, x_2, ..., x_k) for each university. The hazard rate at a specific time point, denoted as h(t), is defined as the ratio of the hazard for events occurring at that time, $h_{event}(t)$, to the hazard for events not occurring at that time, $h_{noevent}(t)$. In simpler terms, it represents the relative short-term risk at time t (StataCorp, 2023),

The Cox Proportional Hazards model assumes that the hazard rate, the risk of accreditation in Biomedical Engineering, for a university with some covariable is directly proportional to the hazard function for a university without the same covariable. Furthermore, these relative hazard functions remain constant over time, meaning the proportional effect doesn’t change from year to year. In other words, the instantaneous failure rate, or short-term hazard function at time t, denoted as h(t), is applicable to all units that have not experienced the event up to that point. It can be calculated as h(t) =-d/dt log[S(t)], where it essentially represents the conditional probability of an event occurring at time t.

The model includes several characteristics unique to each university to account for heterogeneity among universities, including whether a university is listed as a large doctoral university with very high or high research activity in the Carnegie Classification of Institutions of Higher Education in 2020, the count of accredited engineering programs other than BME a university has in each year, and whether the university had both a medical school and at least one accredited engineering program each year. Because universities in "high quality" regional economies will likely be more successful commercially (Casper, 2013), the model controls for the location of the university using census regional division. Additionally, the density of the private biotech industry surrounding the university is also included in the model because existing literature points to agglomeration effects on academic research (Feldman, 2003). These covariables represent a university's capacity to successfully expand into a new scientific field. The model also controls for a university's status as a Historically Black College or University (HBCU) and a land grant university.

Heterogeneity in the reputation of each university is included in the model by grouping universities into categories based on the university's average rank in the US News University and College survey. Finally, the model controls for whether any nearby university has obtained accreditation for a BME program as a measure of a bandwagon effect.

The output from the model identifies coefficients for each covariable in the model. It should be interpreted as the estimated increase in the hazard rate of an event with the risk factor compared to those without the same risk factor. We assume the risk is similar other than that factor and all others included in the model. A higher hazard rate, h(t), means the probability of accreditation is greater at any time t. The larger the magnitude of a positive coefficient, the greater the chance of the event. A negative coefficient means there is a smaller chance of failure. The larger the magnitude of a negative coefficient, the more prolonged survival without accreditation.

A VIF score of 2.02 shows no multicollinearity exists for the variables included in the model. There was no problem with pairwise correlation as established in Table 4, where the only correlation above .6 exists between binary variables, noting when closely ranked universities in the aspirant group and current cohort become accredited. These two variables were not included in the final Cox proportional hazards model but were included in the multi-level logit model described below. Of the 22,786 university years in the model, there were only 124 in which a BME program was accredited.

As a robustness check, I also employed a discrete-time event history logistic model. Simplistic and intuitive, the logistic model is most accurate when events are rare; however, results are not conditional on time, and the effects of changes in time-variant covariables are immediate. The output is given in odds ratios which reflect changes in the likelihood that an at-risk university becomes accredited each year given a one-unit increase in the predictor variable.

The unit of analysis for the logistic model is the university at risk of creating an accredited BME program. The binary dependent variable “out” signals the year a university creates an accredited BME program. Once this happens, the university is no longer “at risk” and falls out of the model. The obvious hierarchical nature of the observations with multiple observations per university over multiple years justifies the use of a multilevel logit model. An intra-university correlation coefficient of .845 which shows highly correlated outcomes for each university year at 95% confidence intervals, and the highly significant likelihood ratio test statistic (p>0.00) validate the use of the multilevel model over the simple logistic model. Due to unit-specific fixed effects, each at-risk university has a different intercept in the model.

The multilevel logit model fits fixed effects models for a binary response with a conditional distribution given random university-level effects. The odds ratios reported for each covariable are useful to measure the strength of the association between risk factors and outcomes. Odds ratios are always positive and report the ratio of two odds: the odds of an event and the odds of survival. Each odds ratio greater than one means an increase in the likelihood that a university will create an accredited BME program, while odds ratios less than one indicate a decreased likelihood of the event. Both odds and odds ratios are monotonic transformations of the probability of failure. Still, simple odds cannot be calculated from logistic regression because coefficients are a log of odds ratio that could have many initial values (UCLA, 2006). For this model, the odds ratio compares the odds of getting accredited given unit-specific and sample-wide covariables in each year to the odds of not getting accredited given the same covariables in the same year. The odds ratio for one covariable stays constant for all values of other covariables in the model (Norton, Dowd, and Maciejewski, 2018). The results are not dependent on time, and odds ratios cannot be compared across models, making the logistic model informative but less useful than the Cox Proportional Hazard model. The results of the logistic model are included in Appendix A.

2.5 Results

The main model shows statistically significant increases in the likelihood of BME program accreditation with variables from all three categories: capacity, reputation, and proximity. Table 5 shows the results for three Cox proportional hazards models used for comparison, with each model adding a group of variables. Model one estimates the strength of the association between accreditation and risk factors identified to measure capacity. Model two incorporates risk factors that measure both capacity and reputation. Model three adds risk factors for proximity. The following discussion will center on model three because tests confirm adding proximity to the model increases the model strength. It is the significance of proximity variables that blur the interpretation of accreditation as a signal of quality.

Several covariable coefficients were significantly different from zero in the full model (Model 3), which incorporated capacity, reputation, and proximity variables. Obtaining a Whitaker grant, having multiple accredited engineering programs, being a designated R1 or R2, having both an engineering school and a med school, being in the very competitive tier, and having a proximate accredited BME program increased the chance of accreditation to different degrees. None of the regional divisions had a coefficient significantly different from zero, so being in a specific regional division does not increase the probability of having an accredited BME program

The observation period covers the evolution of a new scientific area from early stages through growth and maturation. For this reason, one would expect an upward trend in the number of accreditations due to increased interest from students to fill jobs in the expanding BME industry, along with the increase in funding available to academic departments and researchers. The collinear nature of the trends in funding, student enrollment, and expansion of the industry means fixed historical effects are included using the annual federal NIH funding variable. This trend also serves as the baseline hazard function for the Cox proportional hazards model. With each annual increase in funding, the likelihood of accreditation increases.

The coefficient associated with the binary variable that takes the value of 1 when the university is awarded a Whitaker grant is 1.071. We can interpret this to mean a university that receives a Whitaker grant increases the probability of accreditation at any point within the observed period by 191.8% compared to a similar school without a Whitaker grant.

Other results from the model confirm expectations related to capacity for a subset of the sample. As the number of accreditations for one university increases, the probability of BME program accreditation follows suit. This makes sense because universities gain knowledge of the process, so the cost goes down for each added accreditation. In addition, a rating of R1 or R2 and having both a med school and an engineering program increases the probability of BME program accreditation significantly.

The coefficient for having an accredited engineering program other than BME is .110. This means one accredited engineering program at time t increases the probability of accreditation by 11.6%, and having two accredited programs increases the probability of the event by 24.6%. Each additional accreditation adds to the probability of obtaining accreditation for the BME program. Having both a medical school and an engineering school increases the probability of accreditation in any given year by 806% over universities that do not have both curricula. This is not surprising due to the highly technical interdisciplinary requirements of BME.

The highest-rated and perhaps most capable “Top Five” universities all chose not to signal quality by getting BME program accreditation. It is universities that are rated, but not in the Top 5, that become accredited in the greatest numbers. Given there are more than 1750 four-year degree-granting institutions of higher education in the United States[2] (Unirank, 2021), reasonable people would likely agree that every university with an average rating of 122 or higher operates high-quality academic programs. Except for those at the very top, these universities are signaling quality to compete in the higher education marketplace. Given the existing theory surrounding signaling, we would expect no differently. While being in any ranked category seems to have at least some positive effect on the probability of a BME accreditation, the only significant result is for the very competitive rating category, with an average rank of 25-75 which increased the probability of accreditation 126% over non-ranked university programs.

After controlling for variables reflecting the capacity and reputation of a university, the model confirms that the likelihood of an at-risk university obtaining accreditation increases when a nearby university becomes accredited. This is true whether the model controls for geographic location fixed effects or the size of the surrounding metropolitan area. Having at least one nearby university with an accredited BME program increases the hazard rate associated with accreditation. The coefficient for the dichotomous variable “proximate accredited BME” is .588. We can interpret this to mean, all else constant, the probability of BME accreditation increases by 80% when a nearby program receives

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[2] This number does not include community colleges, online universities, and other higher education institutions that do not confer at least four-year undergraduate degrees. The total would be more than 4700 if all higher education institutions were included.

accreditation in the previous year. This means the interpretation of accreditation as a signal of quality is fuzzy, and the signal is less valuable in the marketplace.

The model also points to a bigger problem for researchers interested in agglomeration, as well as economic policymakers. Exclusion of proximate university effects amplifies the effects attributed to geography or industry. Models one and two, which exclude proximity covariables, show significant positive effects related to some census districts and areas with a higher ratio of biotech firms. Once proximity is included, the regional and industry effects are no longer significant. It is important to compare the results of Models 2 and 3 to identify the change in significant covariables. Model two had significant geographic and agglomeration covariables that were no longer significant in Model three once the effects of proximate universities were added to the model. This important finding for agglomeration and ecosystem research should be further investigated. It could mean that research estimating industry-university effects in an ecosystem should include the characteristics of proximate universities to get more accurate results.

As a robustness check, I also ran a multilevel logistic event history model. As expected, directional effects were the same, but magnitudes were different. The logistic model showed significant coefficients of some covariables that did not appear in the Cox proportional hazards model. Notably, accreditation by a school in the aspirant cohort significantly increases the likelihood that a university will become accredited each year, but accreditation in the existing cohort is not significant. This conflicting result is interesting and deserves further research. Perhaps using different sources to assign cohorts would be more illuminating. The log-rank test for difference in survival gives a p-value of p = 0.0061, indicating that universities with proximate accredited BME programs differ significantly in survival from others.[3]

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[3] Using the Wilcoxon option where heavier weights are given to earlier failure times when the number at risk is higher, the p value is p=0.0000.

2.6 Conclusion

Literature tells us that competitive universities build competencies and capacities to differentiate from one another and maximize any plausible competitive advantage (Grimaldi, 2011; Hazelkorn, 2018). Accreditation may positively affect productivity, adding some extrinsic value (Spence, 2002; Terlaak and King, 2006), but the intent of obtaining accreditation for a new engineering program is most likely to signal quality in the higher education marketplace. Given their competitive nature, it is reasonable to believe universities would choose to undertake program accreditation as a costly signal to attract students and faculty, as it is widely accepted that accreditation of academic programs is a mark of quality in the higher education marketplace.

This paper explores the diffusion of academic accreditation and its interpretation as a signal of quality. Patterns of accreditation also give us insight into the diffusion of the new scientific field. The model results show that accreditation is correlated with both capacity and reputation covariables, as expected. However, the proximity variable that identifies nearby program accreditation is also significantly correlated with the event.

This bandwagon effect means competition plays a role in the value of accreditation to the university. As they search for ways to differentiate themselves or merely match leaders, competition incentives universities to expand into a new field and increases the benefit of accreditation.

Accreditation signals attributes of quality not easily observed by outside parties, but there is also a significant geographic bandwagon effect that is not explained by unit or historical variables. The significance of variables representing geographic differences and agglomeration due to the addition of proximate universities deserves more exploration. Model results point to the overestimation of industry effects or other regional characteristics when variables connected with proximate universities are not included in the analysis.

The results of this research clarify the interpretation of accreditation in signaling the quality of an academic engineering program, which is crucial for both prospective students and faculty members considering their academic and career choices. Furthermore, the broader implication of the significance of accreditation by proximate universities reinforces the importance of incorporating proximity-related university effects into models that assess the spillover effects of universities and the factors influencing regional economic ecosystems. This information is expected to be valuable not only for higher education policymakers but also for economic policymakers and researchers studying regional economic ecosystems, as it sheds light on the interplay between educational institutions and economic development.

Tables and Figures

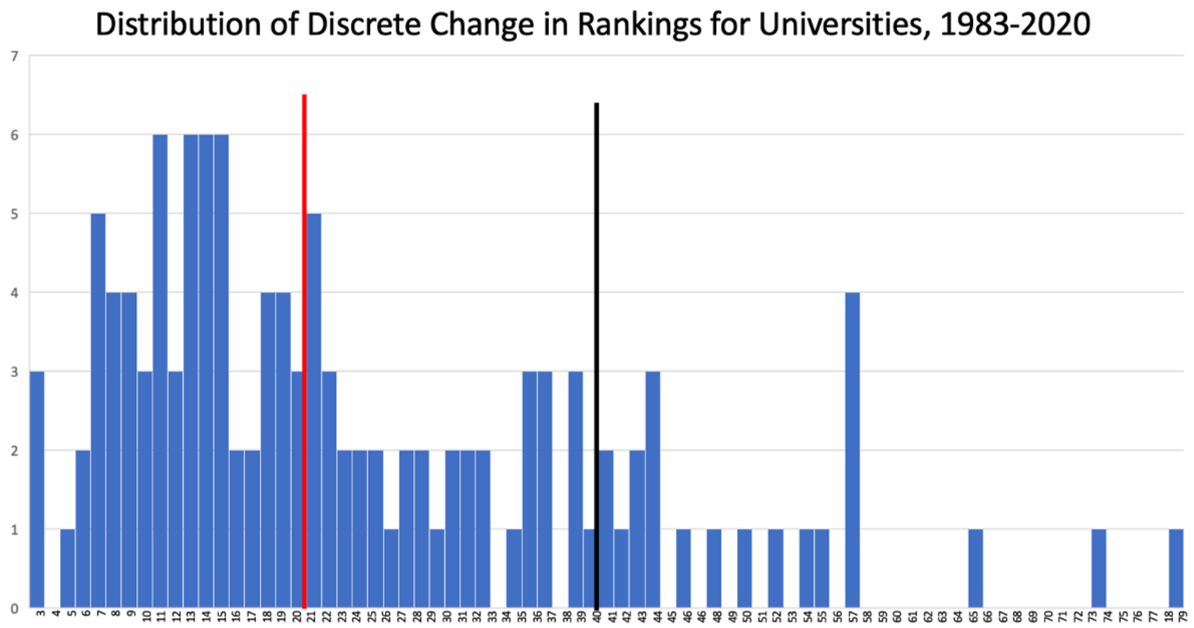
Table 1

Engineering Program ABET Accreditations

Type of Engineering Program	**Number of Accredited Programs**	**Mean Year of Accreditation**	**First Year**	**Latest Year**
Geological Engineering	21	1955	1936	1998
Chemical Engineering	165	1962	1936	2018
Civil Engineering	254	1965	1936	2018
Materials Engineering	64	1969	1936	2016
Electrical Engineering	309	1971	1936	2018
Agricultural and/or Biological Engineering	39	1970	1936	2015
Aerospace Engineering	68	1971	1936	2017
Mechanical Engineering	333	1973	1936	2018
Petroleum Engineering	23	1975	1936	2018
Industrial Engineering	108	1978	1936	2017
Nuclear Engineering	21	1982	1960	2015
Architectural Engineering	24	1985	1936	2016
Engineering Tech	81	1987	1947	2016
Electrical and Computer Engineering	24	1987	1936	2017
Systems Engineering	26	1994	1936	2015
Environmental and/or Marine Engineering	90	1997	1936	2017
General Engineering	141	1997	1936	2019
Computer Engineering	239	1998	1971	2018
Bioengineering/Biomedical Engineering	**124**	**2004**	**1972**	**2018**

Figure 1

Distribution of Discrete Changes in Rankings for Universities



Source: US News and World Report (2023) and Data Science Texts (https://datasciencetexts.com/diversions/college_ranks_race.html)

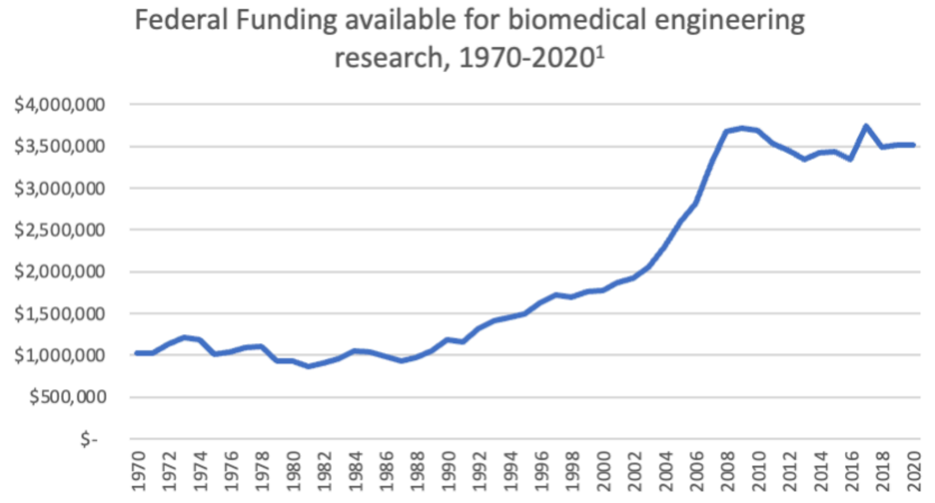
The red line marks 50% of universities and shows the discrete changes in rank, from highest to lowest, was 20 places or less. The black line marks a 40 place change in rank over the 40 year period, averaging out to one place change per year.

Table 2A
List of Whitaker Foundation BME Grants

Whitaker Foundation Grants (1988-2006)

	Leadership Awards	Leadership-Development Awards	Development Awards	Special (Building) Awards
Arizona State University			*	
Boston University	*			
Case Western Reserve University			*	
Columbia University			*	*
Georgia Tech		*	*	
Massachusets General Hospital			*	
Massachusetts Institute of Technology			*	
Pennsylvania State University				*
Purdue University				*
Rice University			*	*
Rutgers University				*
State University of New York, Stony Brook			*	
The Johns Hopkins University	*		*	
University of California, Berkeley				*
University of California, Davis		*		
University of California, San Diego	*		*	
University of Calofornia, Irvine			*	
University of Michigan			*	*
University of Pennsylvania		*		
University of Pittsburgh			*	
University of Rochester				*
University of Texas, Austin			*	*
University of Utah			*	
University of Virginia			*	*
University of Washington			*	*
Universoty of Rochester			*	
Washington University			*	*

Table 2B
Federal Funding available for biomedical engineering research

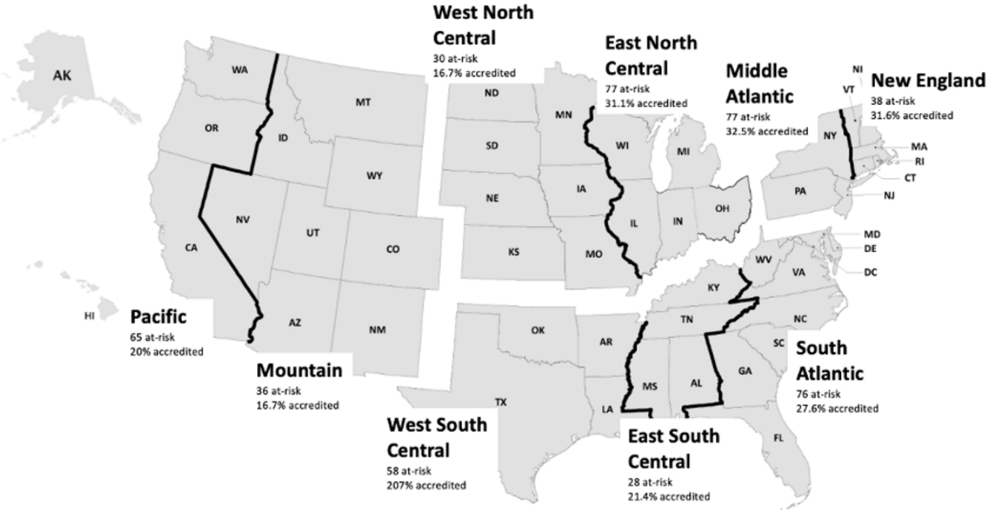


Source: https://www.nih.gov/

[1] Federal Funding shows annual funding available for biomedical engineering research five years before the date on the graph. Accreditation requires at least one program graduate, so funding five years prior has a bigger effect on the likelihood of accreditation than funding in the current year. NIH institutes NIBIB, NIGMS, and NHGRI are included in the aggregated annual funding amounts.

Figure 2

At-Risk Universities Summarized by Census Regional Divisions



	Pacific (Base)	Mountain	West North Central	East North Central	West South Central	East South Central	South Atlantic	Middle Atlantic	New England
At Risk	65	36	30	77	58	28	76	77	38
Accredited BME	0.2	0.167	0.167	0.311	0.207	0.214	0.276	0.325	0.316
Land Grant	0.108	0.25	0.233	0.065	0.103	0.25	0.184	0.026	0.158
HBCU	0	0	0	0.013	0.034	0.179	0.158	0	0
R1 R2	0.338	0.556	0.5	0.402	0.362	0.607	0.447	0.312	0.447
Rated	0.231	0.167	0.267	0.221	0.172	0.179	0.276	0.247	0.342

This figure summarizes at-risk universities by census regional division. The disparity in the percentage of accreditations between regions supports the significance of proximity variables in the model. As of 2022, the Middle Atlantic and New England regions have the highest percentage of at-risk universities with accreditations with 32.5% and 31.6% of universities have accredited BME programs, respectively. These two census divisions also have the highest percentage of population with a bachelors degree according to Census Reporter. The Mountain region has the lowest percentage with 16.7% of at-risk universities with accredited BME programs.

Sources: https://censusreporter.org/profiles/, https://carnegieclassifications.acenet.edu/, https://hbcufirst.com/resources/hbcu-list-map, https://www.abet.org/, https://www.nifa.usda.gov/about-nifa/how-we-work/partnerships/land-grant-colleges-universities

Table 3

Summary Statistics by Rating Category [1]

Summary Statistics by Average Rating

(Range noted if variable is not dichotomous)

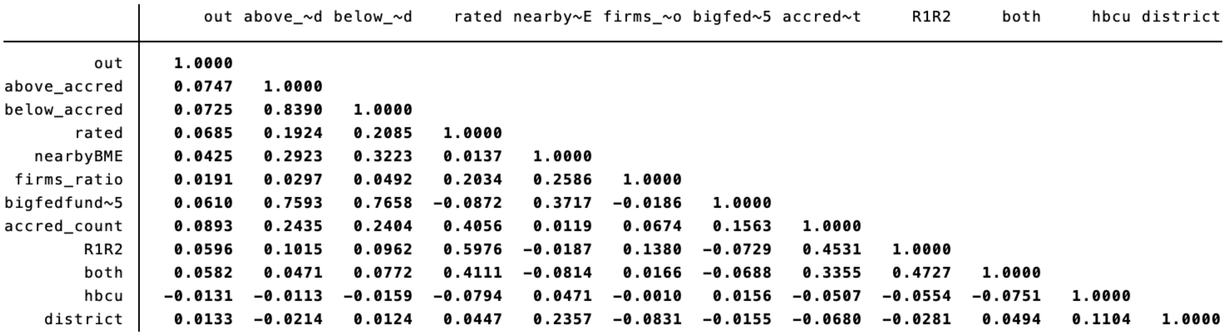
	Sample Population	Top Five (Avg. Rating 1-5)	Super Competitive (Avg. Rating 6-25)	Very Competitive (Avg. Rating 26-75)	Competitive (Avg. Rating 75-127)	Not Rated (No Avg. Rating)
Number of Universities	485	4	23	45	42	371
BME Accredited	0.256	0	0.565	0.8	0.5	0.146
BME Accreditation Year**	2004	n/a	1995	2000	2004	2008
(range)	(1972-2018)		(1972-2015)	(1972-2016)	(1983-2017)	(1976-2018)
Capacity						
Med School	0.299	0.75	0.739	0.622	0.452	0.21
ENG Accreditations	0.918	1	0.87	0.978	0.976	0.906
Both^	0.216	0.75	0.609	0.6	0.429	0.116
Number of Accredited Engineering Programs^	5.687	3.5	6.261	10.244	8.69	4.782
(Range)	(0-24)	(3-5)	(0-16)	(0-24)	(0-19)	(0-17)
Earliest Accreditation	1972	1942	1946	1945	1954	1980
(Range)	(1936-2018)	(1936-1962)	(1936-2015)	(1936-1988)	(1936-2002)	(1936-2018)
Land Grant	0.13	0	0.087	0.378	0.309	0.084
Endowment over $1bil	0.231	1	1	0.778	0.429	0.086
HBCU	0.041	0	0	0	0.023	0.051
R1 R2	0.414	1	1	0.933	0.976	0.245
Firms Ratio	0.058	0.25	0.043	0.067	0.19	0.062
Proximity						
Nearby Count	6.163	16	9.578	7.067	5.07	5.865
(Range)	(0-32)	(0-31)	(0-28)	(0-32)	(0-28)	(0-32)
Proximate University	0.734	0.750	0.957	0.756	0.690	0.722
Nearby BME	0.573	0.75	0.826	0.578	0.595	0.553
Reputation						
Avg Rating*	61.092	2.625	15.152	52.202	101.34	n/a
(Range)	(1.76-127.8)	(1.76-3.61)	(6.8-22.8)	(26.25-75.9)	(77-127.82)	n/a
Top Rating*	50.895	1	8.174	43.711	86.738	n/a
Worst Rating*	75.965	5	22.04	62.667	126.5	n/a
Complete Range	(1-166)	(1-7)	(1-31)	(8-103)	(39-166)	n/a

---

[1] Sources included in previous tables and text.

At-risk universities are included in categories based on average ranking from 1983-2020 in US News. There are 485 universities included in the data set. 122 received accredited in BME. Capacity, Proximity, and Reputation variables are summarized universities in each category as well as the overall sample. Range of variables is included for non-dichotomous variables. Time variant and fixed variables are included. Average rating refers only to at-risk universities that were ranked between 1983 and 2022. The mean BME accreditation year includes only at-risk universities with accredited programs in the calculation. The mean for engineering programs is presented in the table, but the variable was time variant in the model.

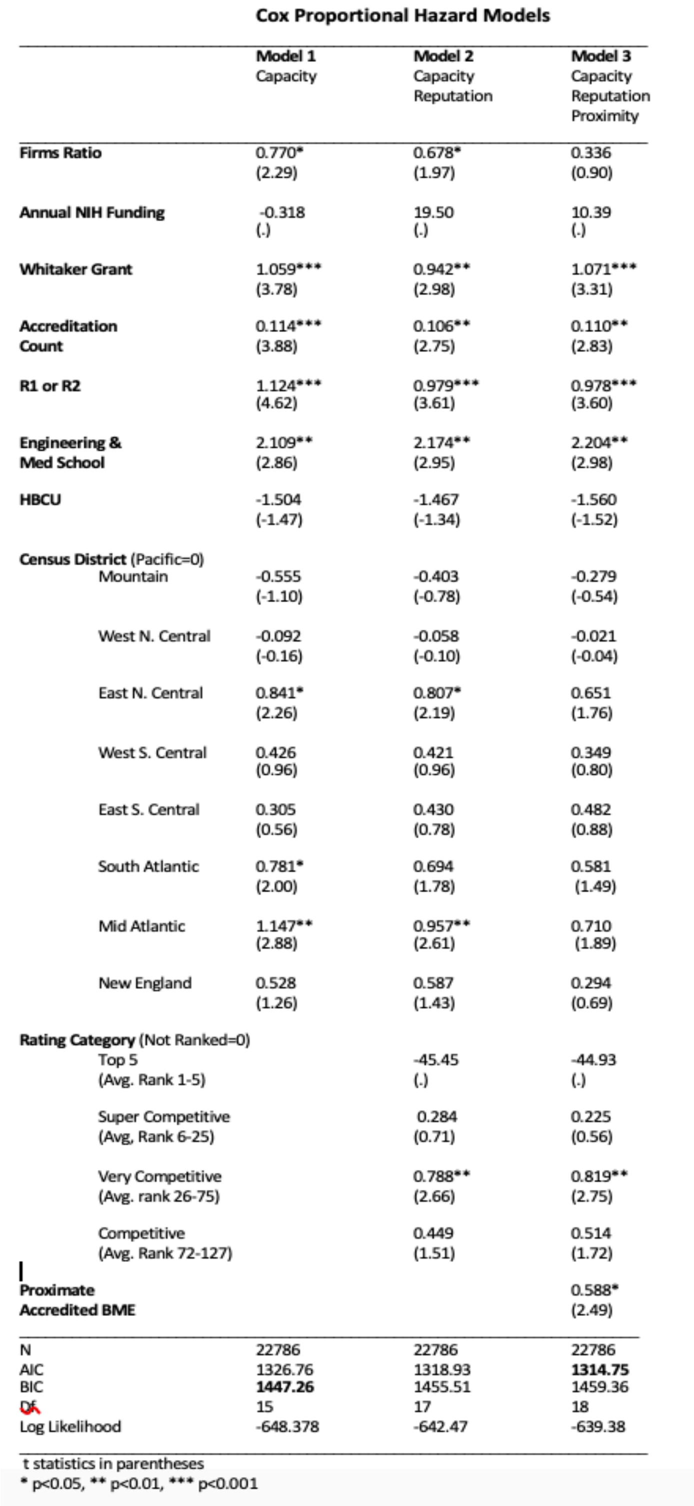
Table 4
Pairwise Correlation of Covariables



```
             |      out above_~d below_~d    rated nearby~E firms_~o bigfed~5 accred~t     R1R2     both     hbcu district
-------------+------------------------------------------------------------------------------------------------------------
         out |   1.0000
above_accred |   0.0747   1.0000
below_accred |   0.0725   0.8390   1.0000
       rated |   0.0685   0.1924   0.2085   1.0000
   nearbyBME |   0.0425   0.2923   0.3223   0.0137   1.0000
 firms_ratio |   0.0191   0.0297   0.0492   0.2034   0.2586   1.0000
bigfedfund~5 |   0.0610   0.7593   0.7658  -0.0872   0.3717  -0.0186   1.0000
accred_count |   0.0893   0.2435   0.2404   0.4056   0.0119   0.0674   0.1563   1.0000
        R1R2 |   0.0596   0.1015   0.0962   0.5976  -0.0187   0.1380  -0.0729   0.4531   1.0000
        both |   0.0582   0.0471   0.0772   0.4111  -0.0814   0.0166  -0.0688   0.3355   0.4727   1.0000
        hbcu |  -0.0131  -0.0113  -0.0159  -0.0794   0.0471  -0.0010   0.0156  -0.0507  -0.0554  -0.0751   1.0000
    district |   0.0133  -0.0214   0.0124   0.0447   0.2357  -0.0831  -0.0155  -0.0680  -0.0281   0.0494   0.1104   1.0000
```

Table 5

Cox Proportional Hazard Model Results (coefficients)



Cox Proportional Hazard Models

	Model 1 Capacity	**Model 2** Capacity Reputation	**Model 3** Capacity Reputation Proximity
Firms Ratio	0.770*	0.678*	0.336
	(2.29)	(1.97)	(0.90)
Annual NIH Funding	-0.318	19.50	10.39
	(.)	(.)	(.)
Whitaker Grant	1.059***	0.942**	1.071***
	(3.78)	(2.98)	(3.31)
Accreditation Count	0.114***	0.106**	0.110**
	(3.88)	(2.75)	(2.83)
R1 or R2	1.124***	0.979***	0.978***
	(4.62)	(3.61)	(3.60)
Engineering & Med School	2.109**	2.174**	2.204**
	(2.86)	(2.95)	(2.98)
HBCU	-1.504	-1.467	-1.560
	(-1.47)	(-1.34)	(-1.52)
Census District (Pacific=0)			
Mountain	-0.555	-0.403	-0.279
	(-1.10)	(-0.78)	(-0.54)
West N. Central	-0.092	-0.058	-0.021
	(-0.16)	(-0.10)	(-0.04)
East N. Central	0.841*	0.807*	0.651
	(2.26)	(2.19)	(1.76)
West S. Central	0.426	0.421	0.349
	(0.96)	(0.96)	(0.80)
East S. Central	0.305	0.430	0.482
	(0.56)	(0.78)	(0.88)
South Atlantic	0.781*	0.694	0.581
	(2.00)	(1.78)	(1.49)
Mid Atlantic	1.147**	0.957**	0.710
	(2.88)	(2.61)	(1.89)
New England	0.528	0.587	0.294
	(1.26)	(1.43)	(0.69)
Rating Category (Not Ranked=0)			
Top 5 (Avg. Rank 1-5)		-45.45	-44.93
		(.)	(.)
Super Competitive (Avg, Rank 6-25)		0.284	0.225
		(0.71)	(0.56)
Very Competitive (Avg. rank 26-75)		0.788**	0.819**
		(2.66)	(2.75)
Competitive (Avg. Rank 72-127)		0.449	0.514
		(1.51)	(1.72)
Proximate Accredited BME			0.588*
			(2.49)
N	22786	22786	22786
AIC	1326.76	1318.93	**1314.75**
BIC	**1447.26**	1455.51	1459.36
Df	15	17	18
Log Likelihood	-648.378	-642.47	-639.38

t statistics in parentheses

* p<0.05, ** p<0.01, *** p<0.001

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CHAPTER 3: DOES INTER-UNIVERSITY CURRICULAR COLLABORATION PRODUCE QUALITY RESEARCH RESULTS?

3.1 Introduction

Research universities occupy dual societal roles. The first and often primary role in the eyes of policymakers is educating the workforce. The second and equally important role is creating new knowledge. It is widely accepted that the end products of both pursuits have societal benefits beyond the traditional university campus, with positive externalities related to university research cited as a key component of innovative regions in the United States (Hausman, 2017; Hazelkorn, 2018). Literature on collaboration argues that sharing and learning from others is vital to unlocking new knowledge and increasing capacity for innovation (Bozeman, Fay & Slade, 2013; Bercovitz & Feldman, 2011; Love and Roper, 2009; Levinthal & March, 1993). Collaboration can describe cooperative relationships between individuals or organizations. This paper explores the role of inter-university collaboration in generating valuable academic research using patent citations as a measure of quality.

The knowledge-based economy brings increased importance to the quality of academic research because new knowledge and innovation created in academic labs diffuse into commercial labs with recent graduates, and basic theoretical research is becoming more intertwined with applied research and development in industry (Link et al., 2018; Feller, 2009). Efforts to increase valuable results from academic research have become a central component of economic policy as regions compete based on their knowledge reserves and innovative ecosystems (Hazelkorn, 2018).

There is fierce competition among research universities for outside funding, well-trained faculty, and academically gifted students. Academic research projects compete nationally and globally for resources, prestige, and recognition on four levels: individual, research groups, departments, and university levels (Deiaco et al., 2012; Feller, 2009). Because scientists are less likely to share competitively valuable information, the Bayh-Dole Act (1980) disincentivized the sharing of basic scientific knowledge and technologies when it enabled universities and other nonprofit entities to patent and commercialize inventions developed in federally funded research. However, norms of open science and institutions that encourage reciprocity can offset this effect (Häussler, 2010). Some have argued that there is too much emphasis on funding research and not enough emphasis on generating capacity through cooperative agreements and arrangements across sectoral and organizational boundaries (Dietz, 2000; Rogers & Bozeman, 1997). In support of this argument, current research grants often emphasize collaboration across academic fields and organizations.

To innovate in a continuously expanding universe of knowledge, researchers engage in knowledge-based and property-based collaborations, which are focused on creating new knowledge and recognizing potential commercial value, respectfully (Landry, Amara, & Lamari, 2001). Most collaborations take place in private industry because more researchers work there (Bozeman, Fay & Slade, 2013). However, the contribution from academic research occurring in university labs is not inconsequential, and it is common for industry researchers to draw on knowledge initially produced by university researchers (Mansfield & Lee, 1996). The percentage of patents developed by university researchers has increased over the past 25 years. Of the 3,932,669 patents granted in the United States between the years 1985-2020, inclusive, 102,258 patents were assigned to universities.[4] (USPTO, 2023). If we focus on the five CPC codes that are regularly connected to patents in the field of biomedical engineering[5], 32,269 patents out of a total of 346,584 patents granted during this same period were assigned to universities (USPTO, 2023). This information is detailed in Table 1. A quick calculation shows that approximately 9% of patents granted during this period in biomedical engineering were created with the involvement of academic researchers

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[4] Number of U.S. patents granted by year is listed in Table 3A in the Appendix.

[5] Five codes are: a61b, a61f, a61k, a61m, and a61n.

at universities. This percentage dwarfs the 2.6% of total U.S. patents created by universities during the same period.

University alliances are formed to explore new technologies, recombine tacit knowledge, and expand the capacity to create new knowledge, both basic and applied (Lin et al., 2012). There are frameworks for exploring how capacity can be expanded on an individual, institutional, network, and global scale (Sewankambo, 2015). The effects of collaboration between industry and universities are well documented, as is the cooperation between individual academic researchers; however, analysis of organization-level inter-university collaboration is mostly omitted from the literature. This omission could be due to its rarity or the difficulty in identifying cases to study. Still, evidence shows that the number of universities collaborating with one another is growing as calls for highly technical interdisciplinary research increase. This should not be surprising. If profit-maximizing firms collaborate, why wouldn't universities seeking a place in the market do the same?

This paper contributes to the literature by defining the difference between curricular and research inter-university collaboration and exploring the effects of both on academic research. Specifically, the research question asks if curricular collaboration in the field of biomedical engineering differs from research collaboration and leads to higher-quality patents as measured by patent citations. The paper will proceed as follows: section two briefly discusses what literature tells us about collaboration, followed by an introduction to the academic field of biomedical engineering. The following sections situate the research hypotheses in the extant literature and introduce the data set and model. The paper concludes with a presentation and discussion of model results.

3.2 Defining the Expected Effects of Collaboration

Collaboration is a cooperative partnership in pursuit of a shared objective (Hagedoorn, Link & Vonortas, 2000). In research and development, it is the pooling of human capital to produce knowledge

(Bozeman, Fay & Slade, 2013). One reason collaboration leads to innovation is that it creates reciprocal trust as well as shared values and norms among research or business network members, known as social capital (Landry, Amara, & Lamari, 2001). The networks and connections that build social capital encourage information exchange and collective learning. The trust created means collaborators spend less effort protecting themselves, further adding to the likelihood of innovation. Social capital may be more critical in heavily technical, scientific fields where faculty need access to equipment and data for conducting research (Gonzalez-Brambina, 2014). Further, the effective communication channels developed by repeated interactions reduce transaction costs across organizations and facilitate the dissemination of research findings because individual actors may share tacit information freely with partners possessing complementary skills and knowledge. This means the long-term collaborative alignments needed for a curricular collaboration should create social capital across university boundaries. If this is true, curricular collaborations should be more fruitful.

Collaboration is not a guarantee for successful innovation. University collaborations may focus on knowledge production, which benefits the organization's reputation, or marketable invention that produces economic value and financial benefit (Bozeman et al., 2013). Many collaborations are initially successful but not sustainable long term, and many are not fruitful from the outset. Contrary to the general population, all collaborations represented in the data set used herein have succeeded in creating new knowledge that is seen as a marketable innovation.

New interdisciplinary academic areas and fields of science seek to analyze complex questions that sometimes require cooperation across organizations, technologies, and geographic borders (Deiaco et al., 2012; Michael & Balraj, 2003). There are benefits to novel combinations of diverse areas of knowledge, so organizations encompassing many disciplines may have more capacity to address complicated societal questions requiring specialized knowledge (Bercovitz & Feldman, 2011). For universities with limited resources or needing more expertise in one important field, collaboration is a viable path to overcome a capability gap and expand into new academic areas (Hellström, 2018; Michael & Balraj, 2003).

Spontaneous researcher-level collaboration is common among academics, but despite competition for scarce resources, organization-level collaboration between universities is less common. Rarer still are sustained curricular partnerships between universities, perhaps due to high start-up costs, leading some universities to suffice by using existing university resources to achieve adequate results instead. While there is a large amount of literature detailing the effects of collaborations between individual researchers, research teams, and university-industry collaboration, there is far less research covering inter-university alliances on an organizational level. A few universities are leading the charge on formal curricular collaborations in important interdisciplinary areas such as biomedical engineering. Often the center of innovative clusters, university research is also believed to be an important driver of local economic growth (Hausman, 2017). The evaluation of collaborative strategies meant to increase innovation and new knowledge is integral for policymakers in the current knowledge-based economy due to constrained university budgets and the need for results to maintain public support of academic research (Sewankambo et al., 2015).

Measurement of university research outputs focuses on new knowledge, human capital, and knowledge transfer, as evidenced by patents, publications, spinoffs, and workforce development (Drucker, 2016). Patents are signs of legitimacy for academic research programs in the marketplace and public opinion (Feller, 2009). Examining the impact of university patents by counting patent citations is one way to measure the quality of university research (Hourihan, 2020). When Bayh-Dole allowed universities to benefit financially from successful patents that result from federally financed research, new expectations were established for university-centered economic development. The legislation changed ownership of knowledge and created technology transfer offices at all but a few research universities in the United States (Grimaldi et al., 2011). The financial incentives and badge of legitimacy associated with patents encourage universities to develop long-term strategies that create new knowledge that can be utilized in the marketplace.

Creating new knowledge commonly requires multiple disciplines and the cooperation of researchers. This collaborative science requires effort spent on coordination, either before or throughout the project, where the cost and benefit of these efforts may depend on the collaboration itself (Wuchty et al., 2007). Collaboration costs increase with the complexity of the agreement and the value of the research results.

In their literature review about research partnerships, Hagedoorn et al (2000) argue that the organizational structure of university-industry partnerships can be formal or informal in nature. This paper builds on this taxonomy to group inter-university collaborations where the involvement of university administration, multiple researchers at both universities and the use of university facilities increases the complexity of the project to move beyond individual researcher collaboration.

Informal collaborative agreements between a university and industry partner are characterized as short-term research endeavors (Hagedorn et. Al., 2000). While not uncommon, research inter-university partnerships are often challenging to identify and measure due to the arrangement's undefined nature or temporary duration. Like individual researcher collaboration, they happen organically. We see evidence of informal collaboration between universities in patents with dual university assignees related to a single grant or study area. While one university bears the cost of applying for the patent, another university also receives credit for "inventional" or "additional" work on a patent resulting from the collaboration. It is also usual that only one of the universities is named on a grant that funds the research project, while the other may be a subcontractor.

The stories behind these informal inter-university collaborations are often as interesting as the results. One story elucidates the 2017 Orbicular Tissue Expander patent assigned to NC State University and Wake Forest University. Richard Wysk, professor emeritus in computer integrated manufacturing at

North Carolina State University, met Anthony Atala, MD, Director of the Wake Forest Institute for Regenerative Medicine (WFIRM), when Atala was invited to speak at a departmental function at NC State. Atala soon accepted a position on the NCSU ISE department's Board of Advisors, and the two began talking about complementarities in their research. Soon thereafter, Wysk received an NSF early-career grant for research in expanding tissue. The two researchers (a medical doctor and a systems engineer) co-created the orbicular tissue expander. The invention received a patent in 2017 with dual university assignees, NC State and Wake Forest. The dual-assigned patent identifies a research collaboration, an inter-university partnership that utilized multiple university resources and shared funding for a single goal but was not long-term.

University-industry agreements are characterized as equity ventures or long-term contractual agreements in the literature. In equity ventures, also known as research corporations, both organizations share risk and cost while capturing economies of scale and increased human capital. Contractual agreements, often called research joint ventures, allow partnering organizations to pool resources to complete research activities (Hagedoorn et al., 2000). Similar to an equity venture, two or more higher-education institutions may charter formal inter-university collaborative agreements to create a joint center for research purposes.

Another example of formal inter-university cooperation can be found with joint degrees, programs, or colleges. These collaborations are created to be sustained for long periods and require faculty to work together to develop a shared curriculum in an academic area. An example of these inter-university curricular collaborations is the Joint Department of Biomedical Engineering at the University of North Carolina at Chapel Hill and NC State University. Chartered in 2003, the joint department shares funding, cost, administration, and leadership, and both universities have facilities dedicated to the joint department on campus.

The start-up costs associated with curricular inter-university collaborations do not exist with individual or research collaborations. When two universities cooperate to create a formal, long-term partnership, such as a joint Ph.D. degree, faculty and administrative units must spend time creating governance rules for both students and faculty. The governance rules must be approved at the highest levels and cover a wide range of topics. For example, the Memorandum of Understanding (MOU) for the Joint Biomedical Engineering Department at UNC-Chapel Hill and NC State University covers topics as diverse and detailed as the listing of both universities on the joint diploma and student parking privileges on each campus. It is important to note the associated economies of scale that exist with long-term agreements; the hefty start-up costs lower the cost of future and sustained collaboration between the organizations, making it easier for affiliated faculty to cooperate across organizations in a research capacity. This is especially true for joint departments with a single cost center.

Table 2 summarizes the characteristics of three levels of academic research collaboration across organizations, starting with researcher-level collaboration. This is the lowest cost and most common level of collaboration and involves cooperation between individuals. Evidence of individual collaboration includes multiple authors on publications, the average number of which doubled on scientific papers published between 1955 and 2000. The most highly cited research, which was once authored by a single author, is normally written by multiple authors more recently (Wuchty et al., 2007). Illustrating the trend, single-author articles made up only 11 percent of the total publications in 2012 (King, 2013). This tendency is likely to continue due to the growing number of academic researchers and publications, as well as faculty promotion requirements tied to publications. Additional motivation to work with others comes from the recent focus on interdisciplinary research by grant-making institutions and the need to share knowledge and research methods to address complex research questions (Michael & Balraj, 2003). While it is likely that multiple researchers will work together on research projects, the choice of collaborator is difficult to predict because it depends on past events and random professional encounters.

Globally, one in four published articles has researchers from different countries, showing this trend extends beyond the United States (White, 2021).[6]

The next level of research collaboration across organizations in Table 2, Organization level research collaboration, requires more than research faculty cooperation. Significant administrative support is necessary for even short-term projects, which commonly have a single funding source but separate cost centers. Shared use of university physical assets such as labs and specialty research tools are likely to be included on some level. Organization-level research collaboration is the most difficult to identify and track because of the projects' undefined nature and limited tenure. This paper treats any patent with multiple inventors in separate locations or dual university assignees and no formal partnership as evidence of inter-university research collaboration. Future research may also use research grants awarded to multiple universities, grant subcontracts, and advisory board members from other universities for identification.

The final category in the table is formal inter-university curricular collaboration. It is a rare but growing phenomenon that can be motivated by one of several reasons: (1) to meet the need of a changing profession, (2) to restructure degree programs and become more interdisciplinary, (3) to respond to enrollment needs, and (4) to enhance the specialized nature of some degree programs (Michael & Balraj, 2003). Like a University-Industry equity-based venture, funding sources and cost centers are often shared for sustained cooperation. The upfront costs of initiating a continuous formal collaboration are substantial. They include the creation of a Charter or an MOU which detail procedures and policies for current and future participants, as well as establishing and maintaining a curriculum to teach students enrolled in the program and graduating with jointly conferred degrees. Formal inter-university curricular collaboration may be identified with joint degrees, departments, or programs. To the

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[6] It would be interesting to see what effect the cancellation of conferences due to the COVID19 pandemic had on individual level multi-author publications.

author's knowledge, a central source for identifying curricular collaboration does not exist. Cost sharing and governance differ by institution, thus requiring further qualitative research to establish trends and similarities.

3.3 Collaboration in the Academic Area of Biomedical Engineering

One of the newest areas of engineering, biomedical engineering, sometimes interchangeably referred to as bioengineering, enjoys mostly favorable public support and has benefited from large increases in federal and private funding over the past sixty years. In his description of the emergence of biomedical engineering (BME). in the United States, Nebeker (2001) defines the field as one that employs engineering principles and processes to solve complex problems in biology and medicine (Nebeker, 2001). BME utilizes the talents of biochemists, cell biologists, engineers, immunologists, materials scientists, and surgeons (Nerem, 1997). Previously housed in departments ranging from medicine to physics and electrical engineering, the field morphed into a standalone interdisciplinary academic area in the late 1960s following advances in engineering and imaging along with a tenfold[7] increase in research grants from the National Institutes of Health in the previous decade. The first leading BME departments were created in universities with strong medical research programs easily leveraged by engineering faculty interested in applying their discipline to human medicine. Agricultural engineering schools also become early entrants into the field, as well as universities with large engineering programs but no medical school (Nerem, 1997).

Given the highly differentiated knowledge structures required to complete research in biomedical engineering successfully, it is not surprising that most academic departments have the capacity to specialize in only a few possible research areas. The high level of tacit knowledge in both engineering and

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[7] Funding increased from $53 million to $430 million in the span of ten years from 1950 to 1960. The NIH also added four new institutes in the same period (NIH, 2022).

human biology may incentivize collaboration on many levels as researchers seek to recombine their tacit knowledge and perform meaningful analysis through exposure to external knowledge (Cohen and Levinthal, 1990). This paper exploits individual and organization level research collaboration, as well as formal curricular collaboration among universities, to analyze how research quality might be tied to all three.

Patent data shows that cooperation among researchers is salient, and organization-level collaborations with industry and other universities are not uncommon in biomedical engineering research. While it is impossible to count the exact number of temporary research-level and organization-level collaborations across an academic field, this is not the case with curricular collaborations. There are ten formal inter-university programs or degrees in biomedical engineering among large research universities in the United States. Table 3 identifies and summarizes basic information such as the number of faculty, year founded, location, and type of collaboration. One of the curricular collaborations, Florida State University and Florida A&M, creates the only joint college of engineering with several departments. Five of the ten formal collaborations form a joint BME department, and the remaining four have joint Ph.D. degrees. Collaborating universities range from one to 122 miles apart, with six being 30 miles or less from one another. At their founding, nine formal partnerships had one university with no hospital, and eight had one university without a college of engineering with accredited programs.[8] Of the ten BME curricular collaborations, two are ranked in the top five academic BME programs in the United States by U.S. News and World Report (US News, 2022). Interestingly, both ranked programs, Georgia Tech/Emory and UC Berkley/UC San Francisco, received at least one large grant from the Whitaker Foundation to support the creation of academic BME programs between 1988 and 2006. Seven of the ten curricular collaborations have patents listed in the data set for this paper. The total number of citations for each patent connected

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[8] Wake Forest University has since developed a school of engineering, and Virginia Tech opened a new university hospital.

to curricular partnerships ranges from 43 to 3808, and the range of the average number of citations per university extends from 9.4 to 76.

3.4 Background Literature and Hypothesis

Reservations about sharing limit the stock of communal knowledge on which scientists base research, so increasing competition between universities has a negative effect on communal knowledge (Häussler, 2010). Given what we know about the benefits of university-industry collaboration, where new sources of ideas are introduced from both partners, we would expect the same results from inter-university research collaboration, but the marginal effect of a curricular collaboration is unexplored. Social Capital Theory argues that relationships between individuals are a resource that allows the exchange of information, which is a prerequisite for innovation. This shared information allows researchers to build on each other's work and achieve results faster because trust is developed quickly when parties are "social neighbors with expected reciprocity." (Häussler, 2010). Repeated collaboration, as in the case of faculty working in a curricular collaboration, should increase researchers' cognitive social capital, increasing the propensity to share and enabling learning that improves organizational performance (Landry et al., n.d.; Levinthal & March, 1993). If innovation depends on sharing, as Social Capital Theory argues, then collaborative departments should be more productive (Bouty, 2000). However, if patents and publications signal tacit knowledge (Häussler, 2010), and novel combinations produce the most innovative outputs (Bercovitz & Feldman, 2011), we might expect the benefits of inter-university collaboration to decrease over time. In other words, trust between collaborators is necessary, but not sufficient, for success (Dietz, 2000).

Research tells us that faculty, rather than university administration, initiate organization-level collaboration (Michael & Balraj, 2003). The literature further suggests that the first motivation is complementary research activity (Mansfield & Lee, 1996), while the second may be access to key research personnel and facilities (Leyden & Link, 1992). Academic research in areas such as strategic management, organizational behavior, and economics have theories surrounding firms' choice to cooperate.

Strategic Management literature claims that firms cooperate in research partnerships to further competitive strategic goals and to maintain or increase market share (Link & Zmud, 1984; Porter, 1986). Inter-university curricular collaboration may enable expansion that attracts undergraduate and graduate students in technical and interdisciplinary fields that are becoming increasingly popular (Michael and Balraj, 2003). To meet student demand in new academic areas, collaboration is one way for universities to assemble resources and gain legitimacy in a new academic area.

Institutional economists may explain a firm's decision to collaborate by building on the Transaction Cost (TC) theory, which argues that reducing costs related to information search, monitoring, and repeated contracting explains the existence of the firm (Coase, 1937). For rational firms interested in maximizing economic profit, aligning goals through collaboration reduces uncertainty and information asymmetry and decreases the transaction cost of the research and development process (Williamson, 1996). Further, when output increases, and economies of scale are exploited, collaboration lowers the unit cost of production. Formal curricular collaboration has high start-up costs but lessens the uncertainty of working together for a sustained period. Repeated interactions reduce communication costs over the life of a project. University leaders must believe sustained collaborative agreements will enhance productive capacity enough to justify the costs of planning and creating governance for a partnership.

A second argument institutional economists favor to explain the firm's decision to collaborate is the firm's Resource-Based View (RBV). of the firm. RBV argues that a firm with rare, valuable, and not easily substitutable tangible and intangible resources can use them to grow and maintain a competitive advantage in the marketplace (Penrose, 1959). It emphasizes the importance of internal resources and capabilities in determining a firm's success. A firm can create a sustainable competitive advantage in the marketplace by focusing on developing and leveraging unique resources. Firms rationally participate in research cooperatives to leverage assets and raise R&D funds (Vonortas, 1997). For a university, tacit knowledge and research methodologies represent valuable intangible resources that complement scarce tangible assets such as lab facilities and hospital access. Collaboration can reduce the effect of scarce resources that would otherwise constrain higher education degree offerings and research capabilities (Michael and Balraj, 2003).

Building on the firm's ability to manage resources, organization behavioralists explain firm collaboration in terms of proximity and organizational learning; two ideas not focused on cost but on expanding capabilities. Arguing firm capabilities are dynamic due to organizational learning means inter-firm collaboration and shared resources are vehicles for growth (Teece & Pisano, 1994). For universities, sharing resources is a way to increase joint capacity to educate students in a popular interdisciplinary field by acquiring needed knowledge and research skills (Hamel, 1991). The literature tells us three critical types of proximity relevant to inter-organization collaboration exist: geographic proximity, organizational proximity, and technical proximity (Knoben & Oerlemans, 2006). When universities collaborate, geographic distance seems important, as evidenced by the ten formal collaborations with an average geographic distance of 32.5 miles and only one partnership as far as two hours apart. Because both cooperating organizations are universities, one might assume relatively high organizational proximity, defined in the literature as a set of routines that allow coordination and include social, cognitive, cultural, and institutional proximities (Knoben & Oerlemans, 2006). Finally, high levels of technical proximity where knowledge overlaps in complementary academic areas is a requirement.

Policymakers have promoted research collaboration to correct market failures in R&D investment, speed up technological competitiveness, and increase the creation and exchange of new knowledge (Hagedoorn et al., 2000). Leaders interested in encouraging curricular or research inter-university collaboration must consider the legal frameworks and support within any ecosystem. Additionally, university-level investments, norms, rules, and faculty members' ability and willingness to collaborate must be considered (Grimaldi et al., 2011). Challenges are likely to be higher when collaborations are created to be long-lasting, but the government can stimulate collaboration through policy instruments that lower the costs of sharing (Sjöö & Hellström, 2019). It must be easy for faculty to work together to justify the higher cost associated with formal collaborations, which is likely to partially offset any expected benefits in knowledge production (Michael & Balraj, 2003). Further, researchers must believe that collaboration will result in an exchange of relevant knowledge because the coordination costs involved in reaching across disciplines and organizations are significant (Bercovitz & Feldmann, 2006).

Learning between organizations is measured in extant literature using products produced and patented inventions and processes (Knoben & Oerlemans, 2006). This paper counts patent citations to quantify the quality of research and innovation in the interdisciplinary academic area of biomedical engineering. Researchers widely accept that patent citation analyses can be used to measure the quality of research and identify novel innovations with market value or important new knowledge that has an unusually large influence on the direction of future innovations (Hourihan, 2020). While patents are not an accurate gauge of total innovation taking place in academic research labs because not all innovations are patented and have an unequal economic impact, they are still tangible evidence of innovation with market value. Patents reasonably indicate the market value of university knowledge and innovation outputs (Audretsch & Feldman, 1996; Drucker, 2016); however, the information introduced in the market but not patented is also a measure of innovative activity (Acs & Audretsch, 1987)

Using a data set of U.S. patents with university assignees, the models herein test for the effects of inter-university curricular and research collaboration on the expected number of patent citations. In addition to multiple inventors in different locations, patents with dual university assignees identify research collaboration because patents with two university assignees are evidence of university-level collaborative innovation (Chen & Fang, 2014). Joint BME departments or Ph.D. programs define curricular collaboration. These models are meant to be exploratory. Literature on collaboration and innovation leads to the expectation that both types of inter-university collaboration should result in higher-quality research.

- *H1: Patents created with inter-university collaboration, research or curricular, will have higher expected counts of patent citations than those without.*
- *H2: Formal inter-university curricular collaboration will have an additional positive effect on the expected patent citation count of biomedical engineering patents.*

The above hypotheses are based on increased human and physical capital availability and the previously explained benefits of collaboration. The potential for productive research stems directly from an organization's ability to comprehend and create knowledge (Levinthal & March, 1993). Similar to the benefits we see with regional agglomeration described by Feldman and Florida (1994), a collaboration between universities decreases the physical and technical distance between research faculty and graduate students from different institutions and facilitates more face-to-face interaction, both planned and unplanned. This fosters the exchange of tacit knowledge (Feldman & Florida, 1994; Knoben & Oerlemans, 2006). In a formal collaboration scenario, the combined organization will have similar rules and contexts in which researchers operate, which should further increase the benefits of collaboration due to the reduction in communication costs (Bercovitz & Feldman, 2011)

Additionally, when two universities work together, the availability of scarce resources increases. The interdisciplinary field of biomedical engineering requires an extraordinary complement of highly technical knowledge and skills, as well as physical laboratories and equipment and access to human subjects who utilize and test processes and inventions. BME curriculums were created to combine a thorough understanding of life science and advanced engineering tools and concepts with the goal of designing medical devices, systems, and processes to improve human health (Linsenmeier & Saterbak, 2020). The need for human and physical capital did not decrease with the formation of the combined field of study. BME departments are often located between the college of engineering and medical school on college campuses. Universities lacking either are at a disadvantage. Inter-university collaboration increases access to expensive human and physical capital that may otherwise be unattainable, creating a shared knowledge base as well as shared physical capital.

3.5 Data and Model

The 990 U.S. patents with university assignees in the original data set have at least one patent citation. Information on individual universities was collected from the National Center for Education Statistics Integrated Postsecondary Education Data System website, https://nces.ed.gov/ipeds/, as well as university-owned websites. Patent information was collected from the US Patent website, https://patentsview.org. U.S. biomedical engineering patents were identified using keyword search terms related to the three main areas of BME, diagnostics, therapeutics, and surgery and rehabilitation: biomedical, nanoparticle, tissue, drug delivery, imaging, medical device, and genome, in the five most common patent classes a61B, a61f, a61K, a61m, or a61N. Research and curricular collaborations were acknowledged after the complete set of patents was identified. Individual university names and forms of collaboration were not used in selecting the patents in the data set. All patent application dates were between 1975 and 2020, with grant dates no later than 2021. Between 1995 and 2013, inclusive, the number of patent applications fell below 30 only once and averaged 40 per year, with 77% of the patents in the data set submitted for approval during these years. The peak year of patent applications that were granted by 2021 was 2007.[9]

The distribution of citations per patent is extremely over-dispersed, with the highest citation count of 1829 and a mean of 51. The large range in citation counts extends the tail of the distribution

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[9] Appendix Figure 2A shows the number of patent applications per year.

beyond what is optimal for this analysis. Based on a visual examination of the data, there is an obvious break in the frequency of patents between 300 and 400 citations. The patents with more than 330 citations listed in Table 4 show only slight differences in the outlier group and the larger patent data set. The mean application year for the outlier set is eight years earlier, the mean research collaboration is lower, and the mean curricular collaborations is higher, but these differences are not statistically different from zero.

Reducing the data set to the 970 patents with between 1 and 330 citations reduces the mean citation count to 40 and the distribution tail to five standard deviations. Figure 1 shows the frequency of citation counts for all 990 collected patents with a red line at the 330 mark. Figure 2 shows the frequency of citation counts for 970 patents after dropping outlier patents with more than 330 citations. I ran the models with and without these outlier observations as a robustness check. The main change in the model was a larger and more significant effect associated with industry-university collaborations.

Table 5 summarizes the data for patents with less than 330 citations grouping patents by the standard deviations of citation counts. By far, the largest number of patents had between 1 and 40 citations. There were 104 patents with a single citation and 689 patents with 40 or fewer citations. Again, the mean value of citations in the model is 40, but the median value of citations is 17. Not surprisingly, all categories had over 80% of patents with multiple inventors. Probability tests reveal that patents in the curricular collaboration group were statistically more likely to have government funding and statistically less likely to have a university-connected hospital. Based on a report on public research and patenting by the American Association for the Advancement of Science which stated that close to 30% of patents have federal funding, the level of government funding is higher than expected for this population of patents (Hourihan, 2020). This difference could be field-specific due to the public support for funding BME research but is likely explained by the large number (53.8%) of single citation patents with government funding. These single citation patents are likely early exploratory research.

A truncated negative binomial regression is employed to model the discrete patent citation count for each BME patent in the data set to evaluate inter-university collaboration's effect on academic research quality. All patents in the data set have at least one patent citation, so the data are left truncated at zero. The negative binomial regression model accounts for the overdispersion of the count data and adjusts standard errors for anticipated heteroskedasticity because the model assumes the variance is a function of its mean plus a dispersion parameter (Ford, 2022). The coefficient of alpha given in the model results estimates the dispersion factor, with anything greater than one pointing to overdispersion. The significant likelihood ratio test for the model confirms that the data are over-dispersed. The coefficient for alpha in our truncated negative binomial regression model is 1.55, and the likelihood ratio test statistic is significant at p=0.00[10]. The model yields the log of the expected count as a function of the independent predictor variables. Coefficients for predictor variables should be interpreted as follows: a one-unit change in the independent variable results in the log of the expected count of citations to change by the coefficient, all else constant (UCLA, 2022).

The main predictor variables of interest in the models identify research collaboration and curricular collaboration in all models except Model 2, and total inter-university collaboration in Model 2 only. The collaboration noted in this analysis is on an organizational level. Inter-university research collaboration is defined by BME patents with dual university assignees and/or multiple inventors in different locations.[11] The model identifies patents assigned to universities with biomedical engineering curricular partnerships as inter-university curricular collaborations. Categories are mutually exclusive. Patents identified as research or curricular university-level collaboration are included in the umbrella category of general inter-university collaboration used in Model 2. Patents with industry or philanthropic

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[10] Statistics given are for Model 1. Models 2 and 3 have similar alpha and lrtest statistics.

[11] If a patent has dual university assignees and only one inventor, it is assumed there was no inter-university collaboration; rather, the principal investigator likely moved.

assignees are identified as industry-university collaboration. Patents with funding from the federal government are also identified in the models.

Also of interest are several binary variables describing each patent's type, the number of inventors on the patent, and the governance of the assigned university. It is common for researchers to collaborate, so it is not surprising that 84% of patents in the data set have multiple inventors, with 26.8% in different cities that could reasonably be treated as unique for commuting purposes.[12] Individual-level collaboration is not the focus of this analysis. It is hypothesized that patents with multiple inventors in different locations and/or dual university assignees represent a higher level of organizational collaboration.

Previous research establishes an expectation that patent citations would differ for process and invention patents (Criscuolo & Verspagen, 2008). My analysis controls for the type of patent by identifying process patents when the word "method" is in the patent title. 43.2% of the patents in the data set are identified as process patents in this analysis. Finally, 59.13% of patents are assigned to public universities. The mean number of citations for the 585 patents assigned to public universities is 50.06. The mean number of citations for the 405 patents assigned to private universities is 53.08.

Model 3 includes a categorical variable, fte_cat, to control for relative university size using full-time student enrollment from 2021 (IPEDS, 2022). The categories for size were based on the mean and standard deviations of the data. There are 118 universities included in the data set, with an average full-time enrollment (FTE). of 25,961 in 2021. There are three size categories. The base category includes 33 universities with up to 20,000 FTE, the middle category includes 54 universities with 20,000-40,000 FTE, and the top category includes 31 universities with over 40,000 FTE in 2021. The smallest university by FTE

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[12] For example, Raleigh, NC, and Cary, NC, are treated as the same location, while Raleigh, NC, and Charlotte, NC, are separate locations. Interestingly, this is higher than the combined 13.6% of patents with inter-university collaboration, of which some are in the same city. This stat is based on the researcher's knowledge of the area. Though interesting, conclusions require more systematic research.

is Rockefeller University, with 215 FTE in 2021. The largest university with a patent in the data set is Texas A&M, with 57,634 FTE in 2021.

Model 4 includes controls for a university's relative research and development expenditure with the continuous variable, *randd_per_fte*. Research tells us relative R&D budgets do not change substantially over short periods of time, so the single-year expenditures from 2021 give a good approximation of each university's relative expenditure levels. Rockefeller University spends the most on research per student by far. The data was obtained from the National Science Foundation HERD survey (ncses.nsf.gov, 2021). Annual expenditure data that focuses on biomedical research would be useful, but it is not available for download over time for a large set of universities. Finally, Model 5 controls for relative university size and relative Research and Development budgets using categorical variables, fte_cat and randd_cat.

Newer patents have less time to gather citations and have unobserved historical events across all units, such as changes in the U.S. patent office and philanthropic and federal funding trends. Rather than including one covariable to control for the application year for each patent, all models include fixed effects for each application year to control for any effects attributed to these events. Standard errors are clustered by the first assigned university to address within-cluster correlation. There are likely "common shocks" for multiple patents from one university, such as funding, star researchers, technology transfer office differences, and facility quality, creating an error with a group structure.

3.6 Results

Results of the zero truncated negative binomial models are presented in Table 7. Coefficients for predictor variables and clustered standard errors are listed for five models that utilize 970 BME patents and analyze slightly different predictor variables in each one. The coefficients given are interpreted so that a one-unit change in the variable results in the log of the expected count of citations to change by the coefficient, all else constant (UCLA, 2022). Therefore, a negative coefficient means the patent with the trait is expected to have fewer patents than a patent without. When the coefficient is positive, the opposite is true. A covariable with this trait is expected to result in a higher patent citation count.

Goodness-of-fit tests disagree on which model is best: Model 1, with separate controls for research and curricular collaboration but no controls for relative size or research budget, and Model 5, which controls for the two types of collaboration as well as relative size and research budget. Since covariables controlling for relative size and research budget use data from one year in the observation period, and the total research budget may differ significantly from BME research funding at a university level, I chose Model 1 as the primary model for the following discussion of results.

The key variables of interest in the model represent research collaboration and curricular collaboration on the university level. Confirming my second hypothesis, the statistically significant coefficient for research collaboration is .39.[13] This translates into a 47.8% increase in expected citations for patents assigned to universities with a curricular collaboration. This means if a patent assigned to a university without a curricular collaboration has ten citations, a patent assigned to a university with a curricular collaboration would be expected to have 14.78 citations, all else constant. Contrary to my first hypothesis, the coefficient for research collaboration is not significant.

Also important for context, the coefficient of the covariable controlling for university-industry collaboration is 0.487. This translates to a 62.8% increase in expected citations for patents with university-industry collaboration compared to those without.

The coefficient of the covariable controlling for government funding was not significantly different from zero. This surprising estimate of the effect of government funding warrants further examination using more detailed data. The variable used in the model was binary, simply identifying whether the

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[13] The coefficient for inter-university curricular collaboration for Model 1 with all 990 patents was .474 and significant at $p < .01$. The coefficient for inter-university research collaboration not statistically significant.

government funded the research or not. One explanation for the result could be that early research projects often receive small government grants, and researchers may patent more minor results due to pressure for positive outcomes. More detailed data with annual biomedical research funding amounts from the government and other sources would yield more useful results. Future qualitative research will address this topic.

Application year fixed effects[14] are mostly statistically significant and negative for all 44 years included in the model. This is not unexpected because time allows for more circulation of results and research that builds on the initial discovery. There are some years with unexplained peaks in patent applications. More research is warranted to explain this phenomenon.

Finally, Model 1 shows that patents assigned (first) to public universities have a slightly lower expected citation count compared to private universities. The statistically significant coefficient of the public university covariable is-0.261, which translates into a 23% decrease in the number of expected citations. The effect of having a university hospital is negative but not statistically significant across all models, and the coefficient for the variable signaling process patents is also not significant.

3.7 Discussion

The results of the analysis show a strong positive effect of inter-university curricular collaboration on the quality of BME research. The effect is similar, though smaller, to the impact of the much-touted and highly studied university-industry collaborations and adds credence to the theory that social capital formed through sustained partnerships leads to more innovative alliances. Figure 3 shows that the model predicts the trend in patent citation counts over time but lacks accuracy on patents with higher citation counts. Given the exploratory nature of the research, the positive effect shown by inter-university curricular collaboration on research quality as measured by patent citations warrants further qualitative

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[14] Detailed in Appendix 3A

research to explore this effect and establish key characteristics of highly successful curricular and research collaborations between universities.

The data set used in the models represents only a sample of academic BME patents and an even smaller percentage of total patents that are assigned to universities. The selection process was not ideal, but it yielded cleaner data than simply downloading all available information. I utilized a keyword term search to eliminate the noise inherent in patent data. This could have created bias due to an unknown systematic exclusion of patents from one university or area of research. A more complete data set of BME patents would alleviate concerns of selection bias. Even then, analyzing patents from one highly technical and interdisciplinary academic area, such as BME, may not yield results generalizable to other academic areas.

Additional information detailing funding levels and sources, as well as research expenditures for university BME programs, would strengthen the results. The literature tells us this information adds to studies on patent quality; however, it is difficult to get this information for specific academic areas in a large data set (Hourihan, 2020). Each individual university, as well as each formal partnership, distributes research funds differently, so the most useful funding data would be specific to BME departments or degree programs. According to the National Science Foundation, annual funding to a specific research area or department is available only on a per-institution basis. The models in this paper attempt to adjust for relative funding levels by including R&D expenditures per FTE for 2021 and using year fixed effects to adjust for common trends in funding, then clustering standard errors by university to control for universities that receive more grants than others.[15]

A new model with detailed funding data would likely lead to different effects that government funding has on patent citations. In the current model, government funding is represented by a binomial

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[15] If some universities are more likely to get funding that affects the quality of their research programs, this effect would show up in the error.

variable. If the patent notes government interest, the variable is equal to one. The negative coefficient means the expected citation count will be lower when government funding is present. The magnitude of funding would make a difference in this interpretation. Many small projects, as well as early research, likely receive government funding. Because early results lead to later funding, there is pressure to file patents that may not have market value or noteworthy innovation (Boffo & Cocorullo, 2019). Small single grants and long-term funding are treated the same in the model, as is the financing of large established projects receiving higher levels of funding from multiple government sources. Readers should be careful not to interpret the negative coefficient to mean that government funding causes lower-quality research.

Due to extreme differences in joint curricular programs, more information on the motivation for the collaboration and characteristics unique to each organization would strengthen the analysis. For example, the BME programs at UCSF/Berkeley and Ga. Tech/Emory are leaders in the field and have received multimillion-dollar philanthropic grants. One would expect research from these programs to be incomparable to patents from smaller, less well-known, and underfunded programs. Further research is warranted to see if one partner gains more than the other and whether it matters what facilities existed before the collaboration. More detailed information about individual university programs could also detail joint grants and subcontracts. This information would likely expand the set of research collaborative relationships. It may be that the current results mischaracterize some observations due to the lack of detailed grant funding information. This could lead to bias in the estimated effects of research inter-university collaboration.

It is common in the literature about university-industry research partnerships to focus on the motivation for the research partnership and the resulting output (Hagedoorn, Link, & Vonortas, 2000). Further investigation into the motivation for collaboration, funding levels, and university research capacity is warranted for a more detailed picture of the benefits of inter-university collaboration. Additional research on sustained collaboration's short- and long-term effects would also be interesting to policymakers as any benefits may decrease over time.

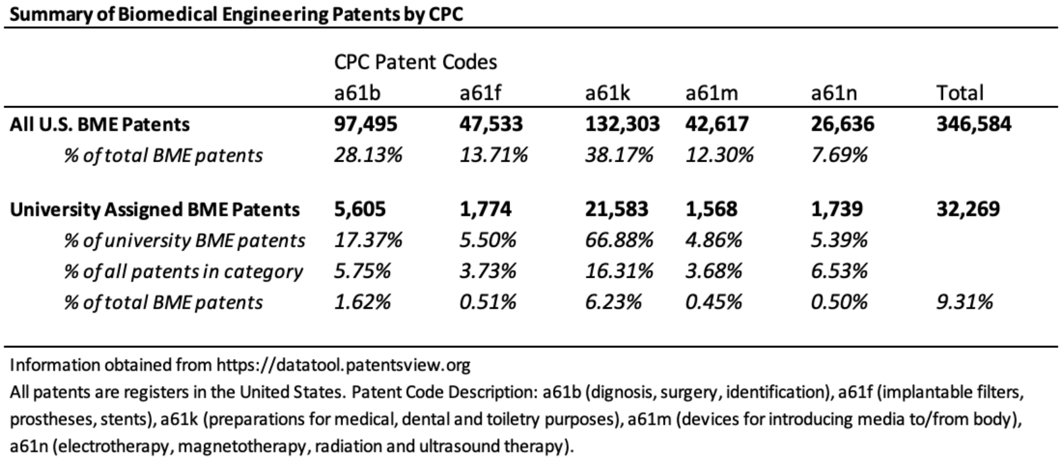
Though patent citations are not a perfect gauge of research quality because there are several other ways to share the knowledge created in the labs of academic researchers, they are one of the few measurable data sources accepted as a concrete measurement of innovation. This paper uses a truncated negative binomial regression to explore the effect inter-university collaboration has on the quality of research as measured by the number of patent citations. Given the results of this model, policymakers interested in spurring new knowledge and innovation should continue to promote inter-university curricular collaboration to achieve these goals. The results are essential for leaders of university systems and policymakers concerned with science and technology in regions surrounding a university.

As previous studies have done, this paper explores the effect of collaboration by analyzing existing data. Future research should identify and explore meaningful trends and patterns in qualitative, university-specific data that might provide valuable insights for academic policy (Hagedoorn, Link, and Vonortas, 2000). Additional exploration of inter-university partnerships will add to the literature on collaboration, innovative ecosystems, and the social capital built with sustained alliances. Moreover, further research adding context to inter-university partnerships leads to a greater understanding of the most fruitful methods to create new knowledge in academia.

Tables and Figures

Table 1

BME Patents Granted 1975-2020, Arranged by Cooperative Patent Classification (CPC).



Summary of Biomedical Engineering Patents by CPC

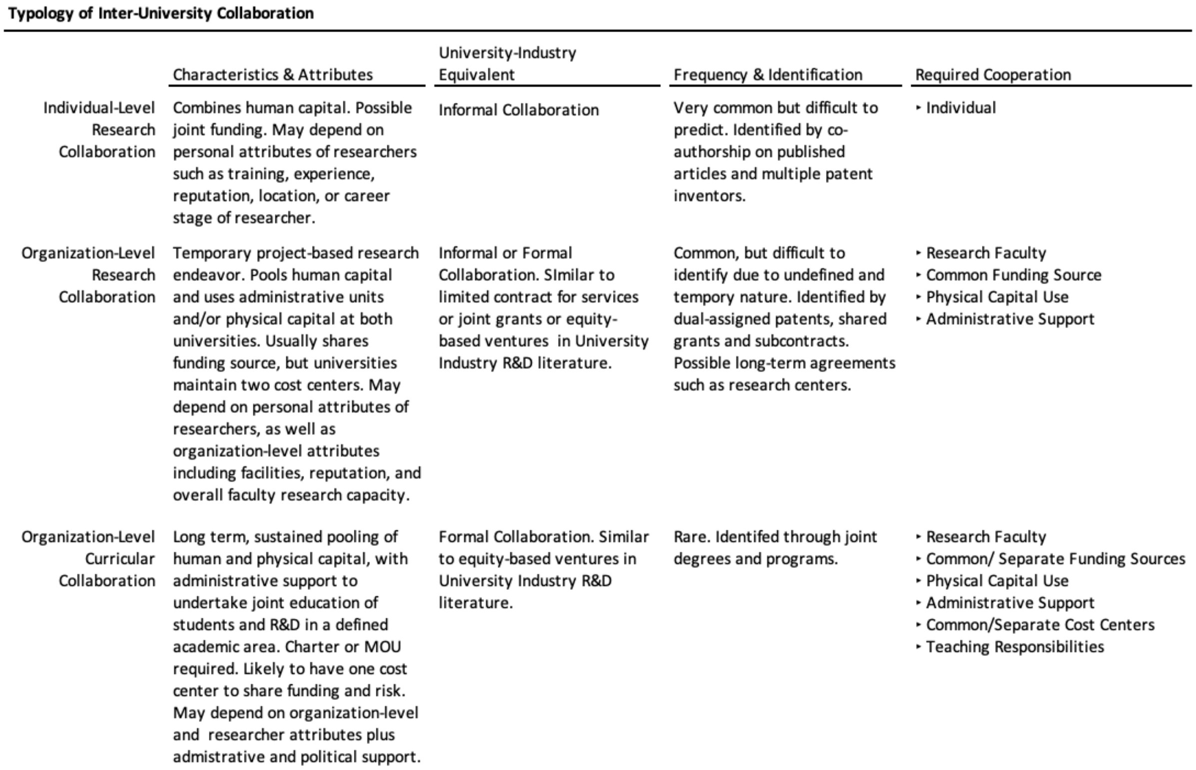
	CPC Patent Codes					
	a61b	a61f	a61k	a61m	a61n	Total
All U.S. BME Patents	**97,495**	**47,533**	**132,303**	**42,617**	**26,636**	**346,584**
% of total BME patents	*28.13%*	*13.71%*	*38.17%*	*12.30%*	*7.69%*	
University Assigned BME Patents	**5,605**	**1,774**	**21,583**	**1,568**	**1,739**	**32,269**
% of university BME patents	*17.37%*	*5.50%*	*66.88%*	*4.86%*	*5.39%*	
% of all patents in category	*5.75%*	*3.73%*	*16.31%*	*3.68%*	*6.53%*	
% of total BME patents	*1.62%*	*0.51%*	*6.23%*	*0.45%*	*0.50%*	*9.31%*

Information obtained from https://datatool.patentsview.org

All patents are registers in the United States. Patent Code Description: a61b (dignosis, surgery, identification), a61f (implantable filters, prostheses, stents), a61k (preparations for medical, dental and toiletry purposes), a61m (devices for introducing media to/from body), a61n (electrotherapy, magnetotherapy, radiation and ultrasound therapy).

Table 2

Typology of Collaboration Levels



Typology of Inter-University Collaboration

	Characteristics & Attributes	University-Industry Equivalent	Frequency & Identification	Required Cooperation
Individual-Level Research Collaboration	Combines human capital. Possible joint funding. May depend on personal attributes of researchers such as training, experience, reputation, location, or career stage of researcher.	Informal Collaboration	Very common but difficult to predict. Identified by co-authorship on published articles and multiple patent inventors.	‣ Individual
Organization-Level Research Collaboration	Temporary project-based research endeavor. Pools human capital and uses administrative units and/or physical capital at both universities. Usually shares funding source, but universities maintain two cost centers. May depend on personal attributes of researchers, as well as organization-level attributes including facilities, reputation, and overall faculty research capacity.	Informal or Formal Collaboration. SImilar to limited contract for services or joint grants or equity-based ventures in University Industry R&D literature.	Common, but difficult to identify due to undefined and tempory nature. Identified by dual-assigned patents, shared grants and subcontracts. Possible long-term agreements such as research centers.	‣ Research Faculty ‣ Common Funding Source ‣ Physical Capital Use ‣ Administrative Support
Organization-Level Curricular Collaboration	Long term, sustained pooling of human and physical capital, with administrative support to undertake joint education of students and R&D in a defined academic area. Charter or MOU required. Likely to have one cost center to share funding and risk. May depend on organization-level and researcher attributes plus admistrative and political support.	Formal Collaboration. Similar to equity-based ventures in University Industry R&D literature.	Rare. Identifed through joint degrees and programs.	‣ Research Faculty ‣ Common/ Separate Funding Sources ‣ Physical Capital Use ‣ Administrative Support ‣ Common/Separate Cost Centers ‣ Teaching Responsibilities

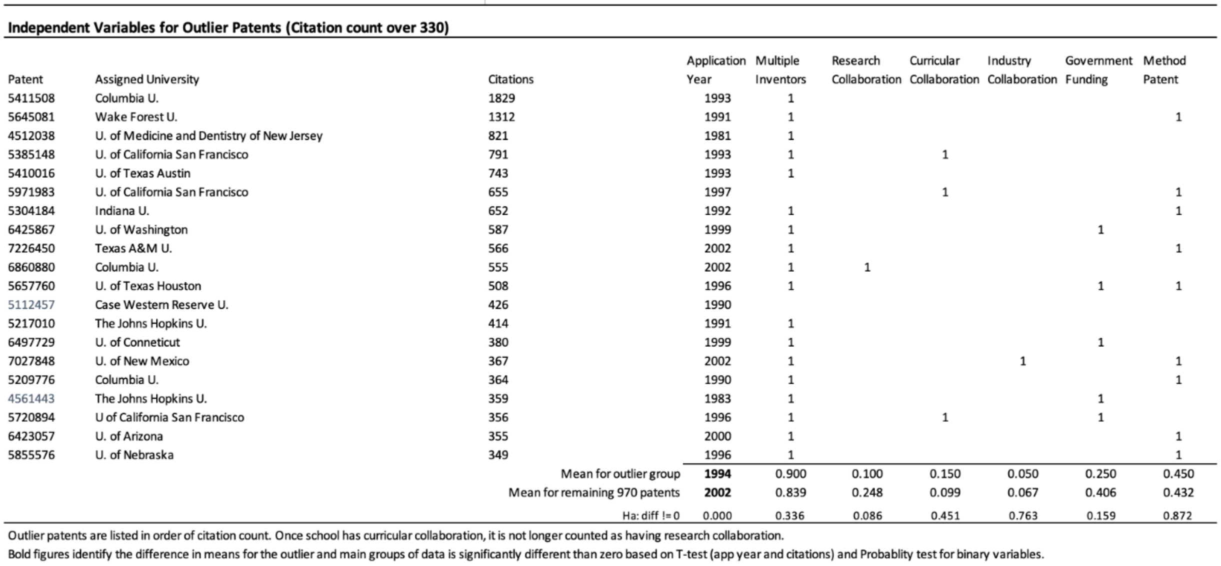
Table 3
Formal Collaboration Biomedical Engineering Programs

Formal Collaboration Biomedical Engineering Programs

	Year Founded	State	Distance	Combined BME Faculty ^	BME Grad Top 10 Rank	NO Hospital (at founding)	NO Accredited Engineering (at founding)	Public/ Private University	Type of Curricular Collaboration	Total Patents in Data Set	Patents Since Curricular Collab.	Citations Since Curricular Collab.	Average Citations per Patent
University of North Carolina at Chapel Hill & North Carolina State University	2003	NC	30 miles	50+		NCSU	UNC	Pub/Pub	Dept	16	13	163	12.5
Georgia Institute of Technology & Emory University**	1995	GA	6 miles	90	2	GA	Emory	Pub/Priv	Dept	14	10	306	30.6
Virginia Tech & Wake Forest University	2003	NC/VA	122 miles	80+		VT	WFU	Pub/Priv	Dept	13	10	254	25.4
Florida State University & Florida A&M University	2019	FL	2 miles	25		FAMU		Pub/Pub	College	1	1	63	63.0
University of North Dakota & North Dakota State University	2017	ND	75 miles	25		NDSU		Pub/Pub	Dept	0	0	0	0.0
Univeristy of California San Francisco & University of California Berkeley*	1983	CA	16 miles	160	4	UCB	UCSF	Pub/Pub	PhD	53	50	3808	76.2
Marquette University & Medical College of Wisconsin	1965+	WI	7 miles	59			MCW	Priv/Priv	Dept	0	0	0	0.0
New Jersey Institute of Technology & Rutgers University	2001	NJ	1 mile	88		NJIT	RNHS	Pub/Pub	PhD	5	5	47	9.4
University of Texas Southwestern & UT Dallas & UT Arlington	1974	TX	17/21 miles	49+		UTD	UTS	Pub/Pub	PhD	9	9	436	48.4
Oregon State University & University of Oregon	2020	OR	49 miles	42		OSU	UO	Pub/Pub	PhD	0	0	0	0.0

* Identifies number of major Whitaker Foundation Grant(s) for BME.
^ Faculty as listed on university websites, December 2022
+ One institution at the time, they have since split.

Table 4
Outlier Patent Independent Covariables



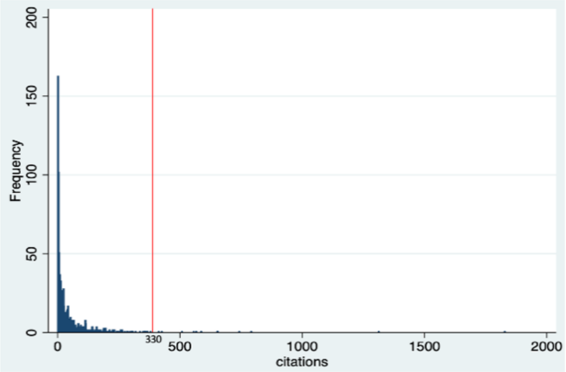
Independent Variables for Outlier Patents (Citation count over 330)

Patent	Assigned University	Citations	Application Year	Multiple Inventors	Research Collaboration	Curricular Collaboration	Industry Collaboration	Government Funding	Method Patent
5411508	Columbia U.	1829	1993	1					
5645081	Wake Forest U.	1312	1991	1					1
4512038	U. of Medicine and Dentistry of New Jersey	821	1981	1					
5385148	U. of California San Francisco	791	1993	1		1			
5410016	U. of Texas Austin	743	1993	1					
5971983	U. of California San Francisco	655	1997			1			1
5304184	Indiana U.	652	1992	1					1
6425867	U. of Washington	587	1999	1				1	
7226450	Texas A&M U.	566	2002	1					1
6860880	Columbia U.	555	2002	1	1				
5657760	U. of Texas Houston	508	1996	1				1	1
5112457	Case Western Reserve U.	426	1990						
5217010	The Johns Hopkins U.	414	1991	1					
6497729	U. of Conneticut	380	1999	1				1	
7027848	U. of New Mexico	367	2002	1			1		1
5209776	Columbia U.	364	1990	1					1
4561443	The Johns Hopkins U.	359	1983	1				1	
5720894	U of California San Francisco	356	1996	1		1		1	
6423057	U. of Arizona	355	2000	1					1
5855576	U. of Nebraska	349	1996	1					1
		Mean for outlier group	**1994**	0.900	0.100	0.150	0.050	0.250	0.450
		Mean for remaining 970 patents	**2002**	0.839	0.248	0.099	0.067	0.406	0.432
		Ha: diff != 0	0.000	0.336	0.086	0.451	0.763	0.159	0.872

Outlier patents are listed in order of citation count. Once school has curricular collaboration, it is not longer counted as having research collaboration.
Bold figures identify the difference in means for the outlier and main groups of data is significantly different than zero based on T-test (app year and citations) and Probablity test for binary variables.

Figure 1

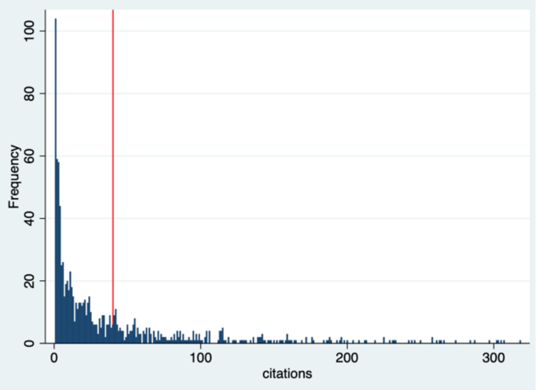
Frequency of Citation Count for 990 collected patents.



The red line marks the break in data after 330 citations.

Figure 2

Frequency of Citation Count for 970 collected patents excluding outliers.



The Red line marks the mean number of citations, 40.13.

Table 5

Summary Statistics for Collected Patents Arranged by Citation Level

Summary Statistics of 970 Collected Patents Arranged by Citation Level (Excludes patents with over 330 citations)

	Obs	InterUniversity Collaboration	Research Collaboration	Curricular University Collaboration	Multiple Inventors	Dual University Assignees	Industry Assignee	Government Funding	Public University as First Assignee	University Hospital	Method Patent
1 Citation	104	0.337	0.250	0.087	0.865	0.038	0.067	0.538**	0.673	0.865	0.384
1-40 Citations	679	0.361	0.264	0.097	0.853	0.044	0.057	0.464	0.592	0.857	0.412
41-98 Citations	171	0.304	0.192	0.111	0.784	0.047	0.052	0.245	0.584	0.830	0.491
99-156 Citations	63	0.317	0.238	0.079	0.809	0.048	0.159	0.317	0.619	0.841	0.349
157-214 Citations	31	0.355	0.194	0.161	0.871	0.065	0.161	0.387	0.516	0.709	0.581
215-272 Citations	17	0.412	0.353	0.059	0.882	0.000	0.000	0.118	0.529	0.882	0.647
273-330 Citations	9	0.222	0.222	0.000	0.889	0.000	0.222	0.333	0.667	1.000	0.444
All Patents	970	0.347	0.248	0.099	0.839	0.044	0.067	0.406	0.589	0.848	0.432

Citation Levels based on data set (excluding outliers) with overall mean of 40.13, standard deviation of 57.055.

The 990 U.S. patents with university assignees in the data set have at least one patent citation. Patent information was collected from the US Patent website, https://patentsview.org. U.S. biomedical engineering patents were identified using CPC classification and keyword search terms related to the three main areas of BME, diagnostics, therapeutics, and surgery and rehabilitation. Keywords included: biomedical, nanoparticle, tissue, drug delivery, imaging, medical device, and genome; with patent classes A61B, A61K, or A61N. Information on individual universities was collected from the National Center for Education Statistics Integrated Postsecondary Education Data System website, https://nces.ed.gov/ipeds/, as well as university-owned websites.

**Government funding for patents with one citation is statistically different than the mean, p>.01

Table 6

Summary Statistics by Inter-university Collaboration

Summary Statisics by Inter-University Collaboration

	Patents	Dual Assigned Patents	Average Citations	Range of citations	Government Funding	University Hospital	Method Patent	Multiple Inventors	Inventors Different Locations	Average R&D per FTE	Range of R&D per FTE
No known Inter-university Collaboration	633	0.000	41.592	(1 - 318)	0.3730	0.8740	0.4250	0.7610	0.0000	25832	(204 - 991604)
Inter-university Research Collaboration	241	0.133	37.137	(1 - 303)	0.4480	0.8550	0.4650	1.0000	0.9880	27540	(0 - 991604)
Inter-university Curricular Collaboration	96	0.094	38.000	(1 - 229)	0.521*	0.667***	0.3960	0.948**	0.2810	72827***	(1144 - 188275)
All Observations	970	0.044	40.13	(1 - 318)	0.406	0.848	0.432	0.839	0.274	30907	(0 - 991604)

Curricular collaboration is true for all patents associated with university after program founding date.

Research collaboration is true for individual patents with dual assignees or different inventor locations for univ with curricular collaboration.

Different location is defined by inventor's city at time of application. Faculty at different universities in the same city share one location.

Table 7

Truncated Negative Binomial Regression Results

Analysis of Patent Citations

Truncated Negative Bionomial Regression

Dependant Variable: Citations	**Model 1**		**Model 2**		**Model 3**		**Model 4**		**Model 5**	
	Coefficient	S.E. (Univ)	Coefficient	S.E. (Univ)	Coefficient	S. E. (Univ)	Coefficient	S. E. (Univ)	Coefficient	S. E. (Univ)
Independent Variables										
Research collaboration	-0.206	0.141			-0.191	0.144	-0.206	0.141	-0.199	0.143
Curricular collaboration	0.39	0.153 *			0.414	0.167 *	0.405	0.167 *	0.305	0.168 +
Inter-university collaboration (any)			-0.018	0.13						
Industry-university collaboration	0.487	0.167 **	0.439	0.164 **	0.494	0.171 **	0.485	0.167 **	0.514	0.169 **
Government funding	-0.128	0.12	-0.137	0.12	-0.129	0.117	-0.129	0.12	-0.161	0.112
Public university	-0.261	0.122 *	-0.186	0.126	-0.301	0.121 *	-0.265	0.124 *	-0.179	0.138
Multiple Inventors										
University hospital	-0.198	0.145	-0.258	0.148	-0.213	0.143	-0.323	0.141 *	-0.323	0.141 *
Method patent	0.019	0.1	0.03	0.101	0.018	0.1	0.018	0.1	0.051	0.101
Application year fixed effects	see appendix table 1		see appendix table 1		see appendix table 1		see appendix table 1		see appendix table 1	
Relative Size of University (2021)										
FTE 20,000-39,999					-0.052	0.114			0.038	0.126
FTE 40,000+					0.111	0.207			0.135	0.211
R&D expenditures per fte (2021)										
2nd quartile									0.167	0.16
3rd quartile									0.319	0.19 +
top quartile									0.389	0.145 **
R&D per fte (2021)							-1.88E-07	6.17E-07		
Constant	5.484	0.146 ***	5.542	0.148 ***	5.499	0.143 ***	5.487	0.146 ***	5.22	0.179 ***
alpha	1.684		1.713		1.679		1.68		1.663	
AIC	8452.457		8462.831		8452.634		8454.374		**8452.235**	
BIC	**8696.321**		8701.818		8701.376		8703.116		8715.609	
ll (null -4355.421)	-4176.228		-4182.415		-4175.317		-4176.187		-4172.118	
df	50		49		51		51		54	
Number of patents	970		970		970		970		970	

** p <.05, ** P <.01, *** p <.001*

+ While not statistically significant above a confidence level of 95%, the result is interesting because the probability that the variable is different from zero is above 90%.

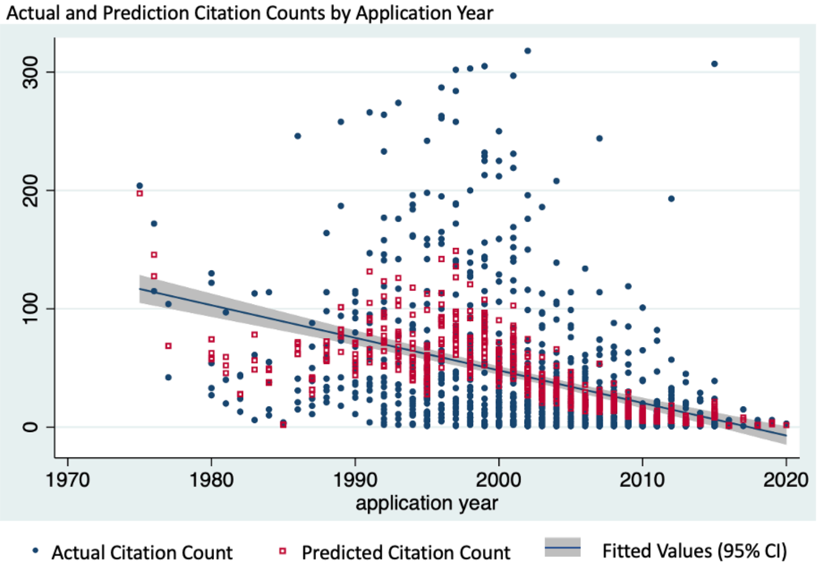
Number of patents was reduced to 970 from 990 after dropping patents with over 389 citations because they are considred outliers. The direction and statistical significance of the main variables did not significantly change. The full model results with 990 patents may be seen in the appendix.

Relative Size of University, based on full time enrollment (FTE), and R&D expenditures per FTE, are based data gathered from the National Science Foundation on the HERD survey for the year 2021.

Due to the large number of years analyzed, application year fixed effects may be seen in Appendix Table 1.

Figure 3

Actual Citation Counts and Predicted Citation Count (Model 1), by application year.



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CHAPTER 4: INTER-UNIVERSITY PARTNERSHIPS: AN INTRAPRENEUR'S PATH IN A UNIVERSITY'S MAKE-BUY-PARTNER PROCESS

4.1 Introduction

Policy, strategy, and entrepreneurship research explore how universities interact with private firms to expand and appropriate the value they create, with much of the research focused on academic entrepreneurs who transfer technology outside of the university. Still, within universities, new highly technical inter-university ventures are created by intrapreneurs operating within an existing organization to increase the quality of research and serve as potential sources of competitive advantage in the higher education marketplace. The benefits of higher-quality research and translational curriculums also extend beyond university participants to surrounding industries and populations and provide knowledge that can be subsequently transferred.

In emerging interdisciplinary academic fields such as biomedical engineering (BME), a global wave of expansion recently required universities to obtain specialized facilities as well as additional human capital to establish new programs. Some university alliances were created to generate new products and commercialize new knowledge, while others were created to further research and build institutional capacity. Encouraging research across university boundaries requires incentivizing individual researchers and reducing the cost of collaboration. Within the limited case studies examined in this research, it appears that intrapreneurs involved in biomedical research collaborations prior to the expansion process build stronger research partnerships that promote program development and further the strategic interests of the university.

Collecting data through multiple case studies, this paper examines how large research universities strategically navigate a common make-buy-partner process to obtain the medical resources needed to expand their Biomedical Engineering (BME) program. In this procedural framework, the intrapreneur, a faculty member functioning outside their conventional role, assumes a crucial role in facilitating the establishment of requisite inter-university partnerships. Each university follows a different path through the common make-buy-partner process. The results of intrapreneurial actions are unique in the form of an inter-university partnership that is created.

This paper contributes to existing higher education and science policy literature by providing context to enhance what we know about the process universities follow when they expand into highly technical interdisciplinary fields. Both external factors and internal motivations are important determinants of paths that are open to an expanding university once a decision has been made to obtain a critically needed resource. This research proposes a common make-buy-partner process universities follow to obtain needed resources, identifies support for theoretical expectations of intrapreneurship within a university, and points out common catalysts and obstacles incurred by existing inter-university partnerships to inform policy. The findings support that intrapreneurs play a pivotal role in nurturing research capabilities through inter-university partnerships. These partnerships are one path in the make-buy-partner process that a university may take to obtain needed resources for expansion resulting in increased capacity for each university involved.

The paper will proceed as follows. A brief discussion of entrepreneurship literature is used to establish expectations and translate dimensions of intrapreneurship to universities. Next, an explanation of the case study methodology and an overview of the make-buy-partner process common to each university is followed by dimensions of leadership, capacity, and institutions that support inter-university partnerships for interdisciplinary research as a practical takeaway for academic leaders and policymakers. The paper ends with a discussion of research weaknesses and areas open for future research.

4.2 From Entrepreneurship to Intrapreneurship, Literature & Theory

Evidence supports that innovation and entrepreneurship come in large part from the mixing of ideas, and studies have shown that collaboration across a broad spectrum of disciplines benefits multifaceted problem-solving and the production of new knowledge (Hausmann, 2017; Bercovitz & Feldman, 2006). Inter-university partnerships are not widely explored in the literature, so the question of how to interpret this activity is important. Prior theory helps define the case and establish a framework for indexing qualitative data (Riege, 2003; Ritchie & Lewis; 1962). Understanding the appropriate lens for scrutinizing qualitative data holds significant importance, as it leverages the power of theoretical insights to put observational findings in context, all while still avoiding predetermined hypotheses (Eisenhardt, 1989)

Literature defines intrapreneurship as the “bottom-up view of corporate entrepreneurship focusing on proactive, work-related initiatives of individual employees to develop new concepts, products, ventures, and business models within an existing organization.” (Antoncic & Hisrich, 2003). Because they are operating within an existing hierarchy, what motivates intrapreneurs likely depends on the entrepreneurial lens of the organization. Should we expect university intrapreneurs to be driven only by the intrinsic motivation gained in creating public value, or does the external recognition and financial gain that comes with the commercialization of new knowledge dominate? If the organization is strategically motivated, there is likely a combination of internal and external factors involved.

Despite the perception that research universities are ivory towers, they are actually entrepreneurial organizations that tend to be innovative and take risks to proactively reach their goals (Morris & Jones, 1999). Like firms, they are seen as direct engines of local economic development but differ due to a lack of a financial profit motive. Large research universities are said to have three missions: teaching, research, and social benefit/economic development. They create public and private value by educating the labor force, generating new basic and applied knowledge, and translating new knowledge to industry, as well as providing extension services and new spin-off firms to the region surrounding the campus. Table 1 compares possible entrepreneurial frameworks that could be used to put a university's activities in perspective. Each entrepreneurial lens is considered based on output goals, organization objectives, decision-making authority, and the likely motivation of the individual entrepreneur and intrapreneur.

As shown in Table 1, one way to think about the entrepreneurial endeavors of a university is in the context of public entrepreneurship. The four universities included in this research are public organizations that face extraordinary pressure to manage resources and create public value (Bryson et al., 2018). Entrepreneurship within the public sector provides an explanation for organizational development and productivity that benefits the public. Universities create value by combining resources in a unique way to exploit opportunities that benefit the region and the public at large, so university intrapreneurs could be siloed as public intrapreneurs with different motivations and characteristics from for-profit firms (Kearney, Hisrich, & Roche, 2009; Morris & Jones, 1999).

Applicable to both public and private organizations, the motivation for public entrepreneurship is the outcome of the actions, not the governance of the organization. It is the creation of public value for citizens by bringing together unique combinations of public and/or private resources to exploit social opportunities (Morris and Jones, 1999). These organizations likely have multiple and diverse objectives that may conflict with one another. Decisions are made centrally, and political considerations often outweigh economics in a deliberation. Regardless, decisions need to be transparent and are often subject to public scrutiny.[16] Individual public intrapreneurs are motivated mostly by societal gain, and we expect them to take risks to overcome bureaucratic obstacles their innovations face. While they do not take big personal or financial risks, intrapreneurs often differentiate their public enterprise (Kearney,

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[16] Though not noted in the literature, it is the author's belief that social media has made the decisions of all organizations more subject to public scrutiny. This factor does not weigh heavily in the analysis.

Hisrich, and Roche, 2009). The public entrepreneurship attributes conflict with many university goals and characteristics. The organizational governance of a large research university has been described as an anarchic hierarchy because decisions are made on many levels, and a central office does not prescribe faculty research and teaching agendas. Additionally, educating and creating knowledge for knowledge's sake has not been the case historically for universities in the U.S (Siegel & Wright, 2015)

While universities, regardless of governance, display characteristics of public organizations, they display characteristics of private entrepreneurial firms, as well. The higher education marketplace has evolved into a competitive ecosystem with unique missions and constituencies that rely on different funding sources without guidance or constraints from a central hierarchy (Hazelkorn, 2018). Because state funding for general operation expenses of universities has decreased, reliance on federal research grants means that regional and local priorities are fading from view. Highly competitive national, regional, and global rankings have incentivized duplication of the successful strategies of leading universities, as they focus on the criteria that may not optimally benefit the local industry or the public.

By focusing on the second and third missions of a research university, the creation and translation of new knowledge, one may decide that large research universities fit better in the academic entrepreneurship category.

Traditionally, research faculty profited from discoveries through recognition amongst peers. As interest in outside funding and commercialization of new knowledge increases, individual recognition also increases freedom for researchers and decreases funding constraints for faculty members. Even traditional industries have become high-tech and strive to innovate using scientific insight and new knowledge, so the potential value of academic research has never been higher (Slaughter & Rhodes, 2004). Bayh-Dole legislation allowed universities and individual researchers to profit from the commercialization of research discoveries. Proponents believed market incentives would ensure new knowledge created with public funds was integrated into the market. The legislation came at a time when public funding strategy switched from direct university grants to subsidizing students through low-interest loans and enabling individual economic actors took precedence over social prosperity in policy making (Slaughter and Rhodes, 2004).

The intent of the Bayh-Dole Act was that technological invention would become the engine of economic development (Wylie, 2011). Academic entrepreneurship refers to efforts undertaken by universities to create and promote the commercialization of new knowledge and entrepreneurial ventures from traditionally non-commercial contexts. Current commercialization efforts have shifted from a focus on patenting and licensing new knowledge to promoting start-ups and entrepreneurship courses (Siegel and Wright, 2015). An academic entrepreneur is an individual employee who spends time creating an external organization or commercializing new knowledge, while an academic intrapreneur is a faculty member who spends time on internal innovation and renewal by creating new centers, departments, or programs involved in the commercialization process within the university (Burkholder & Hulsink, 2022).

We expect academic entrepreneurial decisions to focus on the translation of new knowledge to create commercial and social value with a focus on university-industry collaboration. The expected objectives of the organization center on the translation of research to economic and social contributions outside of the university, and decision-making authority within the organization relies on intermediating networks driven by technology transfer institutions and centers. The motivation for activities is the financial and reputational gain generated by the commercialization of university research (Burkholder & Hulsink, 2022; Siegel & Wright, 2015; Slaughter and Rhodes, 2004). The narrow focus on commercialization makes the application of academic entrepreneurial motivations to all university processes and decisions too limiting.

Operating in a transnational, multi-level system, today's universities seek to build competencies and capacities to maximize any plausible competitive advantage (Grimaldi et al., 2011). Market incentives and neoliberal evaluation measures highlighting individual economic opportunities define the current higher education marketplace in which private and public American research universities compete with thousands of other post-secondary education organizations for resources and students (Slaughter & Rhodes, 2004). New university ventures result in both public and private value. Any financial and nonfinancial private profits are plowed back into research and operations (Siegel & Wright, 2015; Wylie, 2011). Universities are best described by the dimensions of the strategic entrepreneurship category in Table 1 (Siegel & Wright, 2015). In this strategically entrepreneurial organization, multiple levels of outcomes motivate university leadership and faculty to create the entrepreneurial culture of the organization (Hitt et al., 2011). Research universities expand into new academic fields in order to appease stakeholders, create public value, and maximize competitive advantage.[17]

Strategy responds to challenges and constraints in attempting to set an organization apart from the pack. University strategic planning should improve the organization and position it for long run success with both internal and externally focused goals (Eckel & Trower, 2019). We expect intrapreneurs operating in a strategically entrepreneurial organization to focus on growth that creates value for stakeholders in a dynamic and competitive environment (Hitt et al., 2001). The organizational goals attempt to support the twin needs of exploration and exploitation and focus on the development of competitive advantage in the marketplace. Individuals are incentivized by multiple levels of benefits including societal, organizational, and individual, so both internal and external factors influence the decision-making process (Benner & Tushman, 2003; Hitt et al., 2011).

Current intrapreneurship dimensions apply mostly to large firms attempting to expand in a market. The role of large research-intensive universities as strategic actors is undertheorized to the detriment of both scholarship and research policy. Examination of inter-university partnerships adds to

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[17] Prior research showed that competition between universities is a factor in entering and becoming accredited in a new field.

our understanding of intrapreneurship within the context of strategic entrepreneurship in a university (Dodouya, 2009).

Table 2 shows how we can apply the dimensions of intrapreneurship within a firm to a university setting. The eight dimensions detailed by Antoncic and Hisrich (2003) include: new ventures, new business, innovation of services, process innovativeness, self-renewal, risk-taking, proactiveness, and competitiveness. Like a new venture for a firm, an intrapreneur in a university setting can create a new center initiative or department with the university. An example is the creation of a joint biomedical engineering department or an interdisciplinary institute or center on campus. To create a new business, a university intrapreneur might create an external degree program in a new market or create a new revenue-generating program in an existing market. Examples include the Georgia Tech/Emory/Peking University biomedical engineering department in China or the corporate training programs that exist in many business schools. In the area of service innovation, university intrapreneurs might seek to enter new academic fields or create new degrees in existing fields of study. For example, universities often create professional graduate certificates that charge premium tuition and new degrees in expanding academic areas, such as biomedical engineering. Process innovativeness for a university intrapreneur could include online delivery of educational content or co-teaching an interdisciplinary course, while self-renewal in a university setting would include reorganization and renaming of departments. For example, BEAM, the Biomedical Engineering and Mechanics Department at Virginia Tech, was recently created by combining two separate engineering programs. Risk-taking at a university could include the commitment of university, college, or department resources to experimental pursuits such as an inter-university partnership, a research park, or a building devoted to a particular research interdisciplinary initiative. Proactive university intrapreneurs attempt to lead in the higher education marketplace by utilizing new knowledge. Finally, competition exists between universities on several levels, including faculty and student recruitment, local government resources, and research funding which can be global, national, or regional.

4.3 Methods & Data

Prior research established that, on average, faculty collaboration and inter-university partnerships positively affect the quality of biomedical engineering research output. Collecting qualitative data from multiple sources, including published documents and interviews, this case study gives insight and context to events that would otherwise be unexplained. By comparing similar scenarios in which universities create inter-university partnerships in a heterogeneous manner, we can start to understand the process of doing so. Case studies also help us build testable theories in real-world settings (Eisenhardt, 1989; Glazer and Strauss, 1967; Yin, 1984). Each case could stand alone as an independent experiment, but a multiple-case study strategy allows us to identify similarities and differences among cases and identify emergent relationships that enhance the validity of our findings (Eisenhardt, 1989; Baxter, 2008; Yin, 2018). This paper uses qualitative data collected in four case studies to put prior quantitative results in context and enhance our understanding of the events and people involved (Riege, 2003; Crow et al., 2011).

Purposively selecting cases to include rather than using a random sample in a multiple-case study is common. It is important to combine cases that are selected for theoretical reasons rather than statistical reasons. The selection of cases can also be used to reduce extraneous variation in a multiple-case study (Crow et al., 2011; Eisenhardt, 1989). This research focuses on the process followed by four universities, The Georgia Institute of Technology (Georgia Tech), North Carolina State University (NC State), Virginia Polytechnic Institute and State University (Virginia Tech), and Clemson University (Clemson), to obtain resources they deemed necessary to expand their biomedical engineering programs. Table 3 summarizes the characteristics of each university included in this research. Each is a large public research university in the South Atlantic region of the United States. All have respected engineering programs with multiple accredited engineering disciplines and a history of applied research. None of the four universities had an allopathic medical school at the beginning of the process, though NC State had a veterinary school and Virginia Tech had both a veterinary school and an osteopathic medical school at the time. This comparison allows us to exploit the heterogeneity and put the process and motivation for inter-university partnerships in context.

The four universities differ in several categories. For annual research and development expenditure in 2021, Georgia Tech leads the way with over $1.1 billion, while NC State and Virginia Tech spent over $500 million each, and Clemson spent just over $227 million. The range of biomedical articles published between 1980 and 2020 is also large, with Georgia Tech in first place with 3,832 publications, NC State with 2193 publications, Virginia Tech with 1776 publications, and Clemson with 967 publications in the same period.[18] All four graduate engineering schools are highly ranked by US News and World Report, as are the universities. The 2022 graduate engineering school rank for Georgia Tech is 5th, NC State is ranked 25th, Virginia Tech is ranked 30th, and Clemson is 77th. Overall university rank in the same year: Georgia Tech is 33rd, Virginia Tech is 47th, NC State is 60th, and Clemson is 86th.

The inter-university partner for Georgia Tech is Emory University, which is 5.4 miles (20-30 minutes) away.[19] The inter-university partner for NC State is UNC-Chapel Hill which is 31 miles (30-40 minutes). away. Virginia Tech's inter-university partner is Wake Forest University, in Winston Salem, NC, which is 197 miles (3 hrs. 45 mins). away from Blacksburg, VA. Finally, Clemson's inter-university partner is the Medical University of South Carolina (MUSC), a graduate and professional health sciences university in Charleston, SC, which is 240 miles (3 hrs. and 45 mins). away. Each BME joint program or department has multiple research focus areas. Some research in these areas may remain outside BME; for example, biomaterials research is listed in the Department of Materials Science and Engineering and the College of Natural Resources at NC State.

Information collected from public documents found on the internet was the initial source of data. Multiple documents were downloaded and annotated from university websites to get an understanding of

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[18] All publication data was collected from https://www.lens.org/lens/search/scholar/structured using the following setting

[19] All distance and travel times were obtained from https://www.google.com/maps.

how the current biomedical engineering departments operate. In some cases, a brief history of the department was also available. Information on major sources of federal research funding for biomedical engineering and background on major sources of philanthropic support was also obtained from the Internet. Nonpublished internal university documents were also used as source documents.

Multiple interviews with key stakeholders who can provide relevant information produce rich data (Dodourya, 2009). Seventeen semi-structured interviews were conducted in a seven-month period; interviewees were active research faculty, and some were retired faculty or administrators. Multiple interviews of people with either historical knowledge of the process or the current operational knowledge of the biomedical engineering program were conducted for each case. Most interviews were conducted on Zoom, and all were recorded. Names have been left out to protect the privacy of interviewees.

The same set of questions[20] was sent to each interviewee prior to the interview. Certain questions were emphasized depending on the role of the interviewee. Interviewees were allowed to choose the information they wanted to discuss once the interview started. Insights gained from interview observations were compared to expectations gathered from the literature surrounding intrapreneurship and strategic entrepreneurship.

Upon completion, interview transcripts were coded using framework analysis, an organization method used to analyze large amounts of qualitative data (Gale et al., 2013). Quotes were aggregated by categories that emerged during coding. These categories included basic topics that were mentioned in multiple interviews. The initial codes identified data in the following categories: leadership, capacity, internal funding, buy-in/support, process, collaboration, RPT, maintenance, shared resources, goals, recruiting, new field, role model, resistance, external funding, followers, and local external support. A second round of coding grouped by similar topic led to the aggregated data and useful takeaways presented later in the paper.

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[20] The standard set of interview questions and a list of interviewees are included in APPENDIX A.

4.4 The Process of Resource Orchestration

Hitt, Ireland, Sirmon, and Trahms' (2011) Input-Process-Output model of strategic entrepreneurship establishes a connection between external factors, organizational resources, and individual resources, considering them as inputs within the resource orchestration process. The process yields competitive advantage and value that extend benefits to various stakeholders, including society, the organization, and the individuals engaged in this undertaking. The model's central dimension, the resource orchestration process, alludes to activities that leverage current capabilities while simultaneously seeking out new resources capable of generating value. It is this dimension on which this paper builds the make-buy-partner process in Figure 1. The previously mentioned expectations and case study data collected enable the identification of a common process that each university follows in its quest to obtain access to medical facilities and research knowledge. This strategic entrepreneurial decision includes internal and external motivating factors (Hitt et al., 2011; Burkholder & Hulsink, 2022). The make-buy-partner process model herein also adds a temporal dimension to the effect of external factors, dividing them into global and local categories. Observations from this limited case study show global external factors affect the decision to expand, but local external factors played a role in the process of obtaining needed medical resources.

Before this make-buy-partner process began, global external factors and the university's historic path combined to incentivize BME research and/or curriculum expansion. These global external factors, events that all universities and BME academic programs experience, include a significant increase in grant funding from the National Institutes of Health (NIH) relative to National Science Foundation (NSF), the creation of the National Institute of Biomedical Imaging and Bioengineering (NIBIB) at the NIH, big pushes from the Whitaker Foundation supporting biomedical engineering education and the Coulter Foundation supporting translational research, a focus on interdisciplinary funding from multiple sources, and a sustained increase in interest from potential students for BME degrees. All universities had some form of biomedical or biological engineering program before entering the process, some as early as the 1960s. However, all decided to expand within a six-year period between 1995 and 2001. This concurrent timing is not surprising given research that shows organizations seek out environmental munificence where levels of resources can support sustained growth, stability, and survival (Kearney et al., 2009; Dess & Beard, 1984).

Several interviewees mentioned the global external factors that led to the expansion of their BME programs. Before elaborating further, InterviewA of Georgia Tech said, "*There were so many things I could talk about in the way things developed historically across the country.*" InterviewB of Clemson noted, *"Clemson, NC State, Georgia Tech, and Virginia Tech are all engineering schools switching from getting mostly NSF funding and trying to get some of the NIH funding. This is not the case at traditionally liberal arts-focused schools." She added, "The Whitaker Foundation had a whole bunch of grants to fund undergraduate biomedical engineering programs right around 2001. That was when everyone was trying to put their programs together."*

Global external events combined with path-dependent capacities in BME for each university led decision-makers to expand by doing one of three things: they could increase funding to expand "as is," incentivize individual outside collaborations for BME faculty, or get organizational access to medical facilities and researchers. All four universities in this case study made the decision to get organizational access to medical facilities and researchers. Once the decision was made to grow in this manner, the make-buy-partner process of how to obtain the scarce resources was strategic, including both local external factors and internal motivation, institutions, and capacities.

Universities, like other strategic organizations, want to maximize their competitive advantage (Serrano, 2018; Parmigiano, 2007). Each university's path was heterogeneous, but each involved a decision to make, buy, or partner based on the costs and resources available (Serrano, 2018; Boulemole, 2007). Each option is costly for organizations because they may require negotiation and opportunities for things to go wrong (Hitt et al., 2011). The decision of how to obtain the needed resources determines organizational boundaries and the university's future BME research and curricular capabilities (Ulrich & Ellison, 2005; Canez & Probert, 1999; Rosenberg, 1990).

To "make" medical resources, a university could build a new medical school or veterinarian college. Both scenarios have enormous up-front costs and likely require a large infusion of cash from the government or philanthropy. Though neither option was the first step in the process for a university in this study, two schools chose to do so after following alternate paths at the beginning of the process.

To "buy" medical resources, a university could rent space in a research facility or obtain physical access from a non-educational hospital or healthcare system. Simply being on location gives university BME faculty access to doctors and patient data; however, it would be unusual to get access to research and human capital in this type of agreement (Neal et al., 2018). This option has the lowest up-front cost of any in the process and is encouraged in uncertain environments, but it may also be the option with the least potential for sustainability. Using this definition, university-industry agreements would be an example of a university buying access to medical resources. Buy agreements are reviewed and renewed periodically to make sure they are strategically optimal.

To "partner" in this process, a university chooses to align with another university on an organizational level. Having prior collaborations with faculty at another university is a common precursor to an inter-university partnership. Partnerships can be limited or full, with different levels of cost for each. Characteristics of a limited partnership may include some type of joint graduate degree, research collaboration, increased access to physical facilities, and reduced overhead for subcontracts; however, each university maintains its own BME department with separate governance and cost centers. All universities choosing this form of partnership decided to get additional access to medical facilities and research later in the process. If one partner's situation changes, a shift in bargaining power can easily change the value of the limited partnership (Serrano, 2018; Dodouya, 2009).

A full partnership results in a joint department with a single chair that reports to deans at both universities as well as a department advisory board. This type of inter-university partnership is important to the viability of a new field because university departments mobilize human and financial resources, create employment opportunities, and train newcomers (Clausen et al., 2012). Each joint department has a single cost center, therefore, faculty from different home institutions but affiliated with the joint department can collaborate on grants without subcontracts. There is also some type of joint degree, graduate and/or undergraduate. Significant investments are made to incentivize research collaboration and create a unified department for faculty and students. Each university enters the process with different capabilities and follows a unique strategic path. Interestingly, all cases included some form of inter-university partnership.

Figure 2 illustrates the paths each university followed in the make-buy-partner process diagram. The diagrams were constructed using data collected in interviews as well as other written sources documenting the BME program history and current operating processes.

Panel A shows the make-buy-partner process diagram for Georgia Tech. When Georgia Tech (GT). made the decision to expand its research capabilities by obtaining medical facilities and research knowledge, the university was already known for its strong engineering program. They did not have an affiliated medical school or veterinary school.

The GT and Emory partnership began in the 1970s before the establishment of biomedical engineering as a discipline. At the time, the applied research arm of GT received most external funding from the National Science Foundation (NSF). and the Department of Defense. Individual engineering faculty from various departments started focusing on “engineering in medicine,” as it was called at the time and looked for collaborators at the Medical College of Georgia in Augusta and Emory University in Atlanta. The first faculty collaborations came from aerospace engineers interested in cardiovascular applications, electrical engineers working with imaging, cells, and the nervous system, and mechanical engineers interested in developing medical apparatus.

Interested faculty and administration that supported interdisciplinary research at GT felt biomedical engineering represented a new and vital field of study. Though some in the engineering school did not agree with this conclusion, the first inter-university partnership between the public and private universities was called the “Emory Georgia Tech Biomedical Technology Research Center.” GT faculty initiated the partnership and received financial support from both universities’ seed grant programs, as well as support from the state-funded Georgia Research Alliance and local business leaders around the city of Atlanta. This was the first inter-university partnership initiated in the process diagram above.

In 1995, the Whitaker Foundation Biomedical Engineering Program Development Grant was awarded to Georgia Tech and the Emory School of Medicine research center. The Joint M.D./Ph.D. program was approved with the understanding that a joint Ph.D. degree would be created. Whitaker grant recipients agreed to create a BME department when they accepted the award. Two years later, leaders in both universities established the Advisory Committee of Georgia Tech and Emory faculty to address new biomedical engineering opportunities. Don Giddens returned to GT from the College of Engineering at Johns Hopkins, where he served as dean, to chair the committee that developed the joint Department of Biomedical Engineering with the goal of maximizing research and educational opportunities in the field. The joint department was approved in three months, and Giddens was named the inaugural chair. This transformed the limited partnership into a full partnership on the process diagram above. The joint department issues joint graduate degrees; all undergraduates attend GT. The first students enrolled in 2000, and one year later, the Wallace H. Coulter Foundation awarded the department $25 million for naming rights.

Panel B of Figure 2 shows the make-buy-partner process diagram for NC State. When North Carolina State University (NC State) made the decision to expand its research and curricular capabilities in

BME by getting access to medical facilities and research knowledge, it had 12 accredited engineering programs. The precursor to BME was biological engineering, and faculty from this department collaborated with researchers in the university's Schools of Agriculture and Plant Science, as well as the College of Veterinary Medicine. There was no affiliated medical school, but the campus research park, Centennial Campus, had several complete research buildings with corporate and university tenants. Local external factors that played a role in the make-buy-partner decision included regional biotech agglomeration in an area well-known for research. The state-supported NC Biotechnology Center started in 1984. UNC-Chapel Hill had a preexisting biomedical graduate degree, which began in 1968 in the medical school. Duke University, the third research university within 30 miles, was one of the earliest entrants to the field of bioengineering.

The Charter that establishes the "long-term framework for operating a single department" of biomedical engineering at NC State and UNC Chapel Hill explains that the partnership brings together North Carolina's two public flagship universities with a simple mission, "To unite engineering and medicine to improve lives." The partnership charter espoused three core values: innovate, collaborate, and translate, and linked three complementary colleges/schools, UNC School of Medicine, UNC College of Arts and Sciences, and NC State College of Engineering. Administration of the joint department includes two university Provosts, three Deans, and a Department Chair. Applications are submitted through either university, while a single joint BME admissions committee grants admission. Both universities are part of the public University of North Carolina System.

UNC-Chapel Hill's BME department was established in 1992 but was never accredited due to a lack of engineering facilities and faculty. NC State's BME concentration in biological engineering began in 1994, and their BME BS degree began in 2001. NC State's BME program was accredited in 2002. Both universities committed new space and more than $1.5 in one-time funding for the partnership in 2002.

The joint department received a Whitaker Special Opportunities Award in 2004. The joint undergraduate program received ABET accreditation in 2015.

Though there were initially eight graduate tracks, there are currently five research focus areas. To maximize faculty research output, the department rules aim to enable seamless collaboration irrespective of which university employs the faculty member. Faculty and students connected with the joint department have equal access to facilities and services on both campuses, and there is a shuttle that runs between them. There is a single cost center for the department, but it is not independently managed. The department sponsors joint seminars, planning sessions, and research retreats.

Panel C of Figure 2 shows the make-buy-partner process diagram for Virginia Tech. At the Whitaker Conference in 2000, Professors Wally Grant of VT and Pete Santago of Wake Forest struck up a conversation about creating a joint biomedical engineering program to unite Virginia Tech School of Engineering’s biomedical engineering program and Wake Forest Medical School’s biomedical engineering program; It would build on prior collaboration in sport biomechanics. At the time, Wake Forest Medical School’s Engineering department was housed in the Radiology department, and VT’s BME research was housed in the Engineering Science and Mechanics (ESM). department. Despite the main teaching hospital of the Virginia-Maryland College of Veterinary Medicine being in Blacksburg, both schools’ Whitaker Foundation grant proposals had been denied due to lack of expertise in the complementary fields of BME, engineering and medicine.

In the executive summary for the proposed partnership, the stated rationale recognized the new National Institute of Biomedical Imaging and Bioengineering (NIBIB). and increased research funding from the NIH, in general. The goal was to establish a joint degree, collaborative research efforts, and a common administration. Around the same time that VT was discussing the partnership with Wake Forest, they also opened their own clinical facilities on campus, the Edward Via College of Osteopathic Medicine (VCOM). VCOM trains physicians to serve rural and underserved communities, and graduates earn a DO degree instead of an MD degree. Research is not a priority. VCOM has expanded to Spartanburg, SC, Auburn, Al, and Monroe, Louisiana.[21]

The limited partnership agreement spearheaded by Elaine Scott at VT and Santago at Wake Forest created the School of Biomedical Engineering Sciences (SBES) in 2003. The joint program offers Ph.D. and master's degrees in biomedical engineering. The departments in each school remain separate; The chair of VT's Biomedical Engineering and Mechanics (BEAM) department reports to the Dean of the School of Engineering and serves as the chair of SBES. The chair of the BME department at Wake Forest serves as assistant chair of the SBES program and reports to the Head of the Wake Forest Medical School. Each department maintains separate cost centers, faculty, and funding structures, but the program agreement included reduced overhead on research grant subcontracts. The SBES program maintains a single curriculum and classes are often co-taught by faculty from both universities. Students are allowed to spend time at both campuses during a required clinical rotation. Many SBES primary and affiliated faculty are also associated with the NIH Comprehensive Cancer Center at Wake Forest.

The SBES program has benefitted both universities by enlarging the recruiting area for the graduate BME programs and providing a larger presence on the national stage. The primary purpose for the partnership is curricular. In 2018, the Carillon School of Medicine officially became a college of Virginia Tech. According to interviewees, VT BME faculty are strongly encouraged to collaborate with Carillion faculty. With the creation of the undergraduate degree in BME, VT faculty also have increased teaching responsibilities that pull them away from SBES. This has caused a misalignment of goals between the two groups of faculties.

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[21] VCOM has partnered with Bluefield University, a small liberal arts university in Virginia, to offer a non-medical graduate degree in biomedical sciences. The degree has a "strong emphasis on human medical and clinical applications." They also have a collaborative teaching agreement with Averett University for a graduate degree in applied health care data analytics.

Panel D of Figure 2 shows the make-buy-partner process diagram for Clemson. With The first PhD awarded in 1963, Clemson celebrated the 50th anniversary of their Bioengineering[22] program in 2022. While bioengineering has a long history at Clemson, the program formally accredited as Biosystems Engineering became a department with undergraduate and graduate degrees in 2006. Clemson's bioengineering program became accredited in 2009. Several events preceded this milestone to create Clemson's "Three-legged stool," which includes programs on the main campus, Charleston, and Greenville.

South Carolina was one of the first five states to be named in the Established Program to Stimulate Competitive Research (EPSCoR). It also participates in the NIH IDeA program, which aims to broaden the geographic distribution of NIH funding for biomedical research. The state of South Carolina has three research universities, the University of South Carolina in Columbia, the Medical University of South Carolina (MUSC). in Charleston, and Clemson University (Clemson). The SC BioE Health alliance started in 1984 and received a good portion of the state's $79 million in tobacco settlement money in 1998.

Clemson engineering faculty often traveled to MUSC and other area medical facilities to do "bench work." One of the first notable collaborations with MUSC began with Clemson ceramic engineering faculty and researchers at the dental school. To institutionalize existing faculty collaborations and gain a competitive edge in the discipline, the university expanded the bioengineering (BioE). program by creating the Clemson-MUSC Bioengineering program in 2003. With a slogan to "exemplify collegiality,"

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[22] It is commonly said that biomedical engineering is a discipline of bioengineering, but the terms are often used in place of one another. The Whitaker foundation favored "biomedical engineering," so many programs seeking funding from the philanthropy used this term. When explaining the difference between bioengineering and biomedical engineering to undergraduates, the BME Life video series states, "Though there are technical differences between them, both bioengineering and biomedical engineering are used interchangeably and overlap in many areas. Bioengineering uses engineering principles to solve problems in all life sciences and medicine while biomedical engineering focuses on medicine and healthcare." https://www.youtube.com/watch?v=gGnwUnCy_S0 Biological engineering also falls under the umbrella of bioengineering.

the limited partnership was renewed in 2013 and is extended annually. Currently, there are seven Clemson faculty members located at MUSC campus, and all students in the program are from Clemson. Some courses are taught by MUSC faculty.

The former chair of BioE at Clemson called CUBEinC, the second expansion of the BioE program, a hybrid model. CUBEinC is the only example of a university “buy” decision in this case study. Faculty members occupy the 4th floor of the Patewood Medical Campus of the Greenville Health System Clemson. CUBEinC, which stands for Clemson University Biomedical Engineering Innovation Campus, started in 2011. It is located 40 minutes west of the main campus, in Greenville, SC. Clemson pays rent for the space in the Patewood Medical Campus, which is owned by Prisma Health, South Carolina’s largest private, non-profit healthcare system. Prisma also runs USC’s medical school on the same campus. The Patewood facility specializes in orthopedic surgery and obstetrics. Clemson’s SC TRIMH program, funded in 2022 as part of the IDeA program by the NIH Center of Biomedical Research Excellence (COBRE), has a strong presence here. The “clinical partner” named in the funding grant is PRISMA Health System, and the funding goal is to train future researchers and tech transfer.

In 2023, Clemson announced it would build a new veterinary school on campus. Initial grants for the veterinary school include $103 million from the state of South Carolina. One factor in this expansion is likely NIH’s increased funding for animal research and the implications it will have on the bioengineering program at Clemson.

4.5 Theoretical expectations supported by case study data

Universities obtained needed medical resources by following different paths that all included an inter-university partnership. Organizations use partnerships to leverage resources and pool talent to tackle challenging issues. They also allow for professional collaboration. Following Eddy’s (2010) precedent, this paper refers to "inter-university partnerships" as organization-level alliances between higher education institutions. These include strategic alliances and joint ventures. Individual-level faculty pairings across institutions are referred to as "collaboration" rather than partnerships (Eddy, 2010). Significant evidence has emerged from this research that prior collaboration may be the primary motivation for successful inter-university research partnerships.

A key tenet of creating partnerships is that the combined benefit exceeds that which can be obtained alone; the classic economic scenario in which partners engage in trade to create a win-win situation (Cabral, Mahoney, McGahan, and Potoski, 2019). Evaluation of partnerships is often based on output measures, which may not be optimal in this scenario (Eddy, 2010). While defining failure is beyond the scope of this research, this paper attempts to identify structures and highlight institutions that promote the success and sustainability of inter-university partnerships that result in a shared curriculum or increased levels of collaborative research. Observational data collected herein confirms that partnerships have high upfront costs, require administrative oversight, and likely impact the whole organization; therefore, the creation of sound policies for new inter-university partnerships and the required commitment of resources is important for university leaders.

The extant body of research pertaining to strategic entrepreneurship and intrapreneurship within the organization has given rise to the following expectations about the make-buy-partner process examined in the case study: university capabilities are path-dependent, intrapreneurship operates at the organizational margins and depends on administrative support, the process of obtaining resources is strategic, while collaboration is initiated organically and support by careful planning. Each expectation is supported by data obtained in interviews and used to provide context.

4.5.1 Capabilities prior to the make-buy-partner process are path-dependent.

Scarcity forces organizations to choose what technologies to have in-house. Internal research and external knowledge acquisition are complementary innovation activities that depend on the firm’s strategic environment (Brekke, 2015; Mustar & Wright, 2010; Boulemole, 2007). The biggest predictor of a make-or-buy decision is resource limitation and lack of technical personnel (Cassiman & Veuglers, 2006). However, a simple make-or-buy decision process does not accurately describe how universities obtain medical access. High levels of intrinsic knowledge required to do research in BME mean external partnerships are also beneficial (Cohen & Levinthal, 1989).

Each university enters the make-buy-partner process with different capabilities. InterviewC at Wake Forest Medical School outlined the endeavor to secure external funding for the expansion of their well-established department within the Medical school and the subsequent choice to form a partnership with another university in a straightforward manner, saying, "*They did not have an allopathic med school that was strong in research, and we did not have an engineering school. The motivation was for a big medical school to partner with a big college of engineering.*"

The circumstances varied significantly at Georgia Tech. InterviewD, explained, "*We had a joint research engineering research center that was a $30 million dollar center. That started a couple of years before the department was going to start, but that really provided a lot of momentum for the establishment of the partnership.*"

University capabilities are dependent on past decisions and current external factors. Each university must approach the process of obtaining medical resources strategically. Choosing to partner with a peer institution is costly but should increase future capacity for learning and research.

4.5.2 Intrapreneurship operates at organizational boundaries.

Research faculty often search for new topics at the frontier of their fields (Antoncic and Hisrich, 2003). A common motivating factor in the development of inter-university partnerships is the existence of prior research collaborations between organizations. All inter-university partnerships that led to a substantial increase in collaborative research were initiated and shepherded by at least one intrapreneur who was also an existing faculty member from engineering.

Before Troy Nagle became the Inaugural Chair of the joint NC State UNC BME department, he worked in the microelectronics group with UNC researchers. He came to NC State from Auburn University, holding a Ph.D. in electrical engineering and an M.D. He described his interest in an inter-university partnership: "*I took a tenured faculty position at NC State in 1984, which was the best home for me given my engineering and medical background. I had recently gotten an M.D. degree, so I could work on medical projects and medical electronics. I was working with the group in Chapel Hill, and I was participating in their programs and student projects and all kinds of things over there."*

Clemson University invested early in biological engineering, and much of the bioengineering research taking place before the inter-university partnership had been collaborative. Former Chair of the Clemson-MUSC joint BME program, Martine LaBerge, explained the intent of the partnership saying, "*People have been working together since the sixties. We were traveling to hotels to do bench work at MUSC. The intent [of the partnership] was to formalize this collaboration between researchers and provide a platform and a net. It allowed us to have labs. It is meant as a collaboration space."*

Researchers must see the value of costly activities. It is most often faculty curiosity and interest in new research that initiates fruitful collaboration in a new area.

4.5.3 Intrapreneurship is an example of bottom-up innovation within an organization, so leadership approval is required.

One unsupportive administrator can make the intrapreneur's path much more difficult. Approval and support from university officials, including Deans and Provosts, is necessary but not sufficient for success. Determinants of an environment conducive to intrapreneurial behavior include management support that tolerates failure and work discretion that gives freedom from excessive oversight (Hornsby, 2002)

Perhaps Don Giddens, the Inaugural Department Chair for the Coulter Department of BME at GT and Emory, explained it best: "The role of upper administration is to buy into the vision and then enable it." While his GT colleague, Interview D, explained, "*You have to get the blessing of and work for people that are not directly involved in the collaboration, right? So, to them, it may not be apparent why we need the investment or resources and effort. Do they really appreciate the sort of nuances or requirements of offering a degree like BME that is so interdisciplinary in every aspect?"*

InterviewB at Clemson, discussed the role of leadership more specifically, "*It is important for admin leaders to be on board because even once the partnership is established, there's continual maintenance on the relationship. … when MUSC gets new leadership, Someone has to make sure the new people know that we're there and we have a collaborative program and things like that."* InterviewE, BME faculty member at NC State, explained how administration could be helpful in clearing up the hurdles saying, "*Administratively, it was a nightmare. The provost would usually come in and say, "Fix it." Then the administrators would fix it. So, [his support] got them behind us, and a lot of administrative hurdles were overcome this way."*

4.5.4 The process of obtaining needed resources is complex.

Decisions depend on internal motivation and the local external environment. Resource munificence can be increased by business and regional government support of a field or project, while grant funding enables options not available before. Internal motivations for universities include better recruiting of top research faculty and students and more grant money. Both increase competitive advantage for the organization and result in more freedom for faculty. Because decision-makers consider transaction cost and resource-based capabilities in a make-or-buy decision, the process should be evaluated using strategic management theories (Serrano, 2018). Further complicating the decision are plural sourcing options in which simultaneous insourcing and outsourcing take place (Parmigiano, 2007).

Since leaving NC State after her instrumental role in creating the joint BME department, Fran Ligler is the Eppright Chair in Biomedical Engineering at Texas A&M. She explains that her role at the institution involves enhancing collaborative research efforts with the veterinary school and various medical facilities throughout the state. She elucidates that BME faculty working away from campus are there by choice, saying, "*BME faculty who are down there want to be there... It is a huge center that gives them access to patient samples and patient data... We're growing that footprint from our department even though it's an hour and a half drive away. We only have a few collaborations with our medical school here because they don't do much research."*

Based on observations, several common factors lead a university to invest in an inter-university partnership versus simply making or buying the resource. Table 5 summarizes the determinants that incentivize a university to follow different paths through the make-buy-partner process. Based on observations, they are not intended to follow a linear progression or constitute an exhaustive list. However, each determinant present in a scenario makes the endpoint more likely.

While each university chose to form a partnership at some stage in the process, other paths were also followed. In both cases of a "make" decision, the universities received major state funding grants and political support to create their own medical facilities staffed with newly hired university faculty. Examples of newly created research-focused medical facilities include VT's Carillion School of Medicine and Clemson's Veterinary School. The upfront cost of each new venture means the benefits to the university must have far exceeded the boundaries of the BME program, but the effect on the process of obtaining medical facilities supplants the need for other options and is, therefore, relevant.

Alternatively, buying short-term or frequently renewed access to medical facilities is the lowest-cost path for universities looking to obtain medical facility access. Factors that lead a university to do so include uncertainty and limited state support for more expensive options. This option is especially attractive when a robust private healthcare system or industry partner is present in the region. It can be a cost-effective way to expand an undergraduate BME curriculum with little need for advanced research collaboration. Only Clemson chose this path as part of the process to expand access to medical facilities in this case study. There are several examples of university-industry interactions designed to commercialize new knowledge that are not part of this research.

The choice to partner with another university to increase access to medical facilities and researchers is most likely when prior research collaborations exist between peer institutions that have complementary resources. While major grants supporting a new discipline may be instrumental, the willingness of influential faculty to take on the role of intrapreneur is also key. Intrapreneurs must believe and convince the administration that the partnership will fulfill individual, program, and university goals, which may include accreditation aspirations and expansion of a graduate research program. Uncertainty regarding university projects and goals, differences in organizational governance, and a focus on the expansion of curricular capabilities or obtaining outside funding seem to lead to a limited partnership scenario. A full partnership, on the other hand, is more likely when significant resources are put towards increasing researcher collaboration and capacity for the long run. Full partnership determinants also include proximity to partner campuses and full access to facilities and benefits on both campuses for students, faculty, and researchers.

4.5.5 Research collaboration is organic, but it is augmented by organizational planning.

Collaboration between researchers at different universities can be incentivized by organizational institutions that are detailed, well-planned, and flexible. Most critical barriers to partnerships come from information and cultural mismatches between organizations that have different incentive structures (Cabral et al., 2019). Universities have three missions: education, research, and outreach/engagement.

Medical schools have a fourth operational mission, high-quality healthcare and clinical services, which often supersedes others (Burkholder and Hulsink, 2022). A difference in organizational culture and misalignment of goals creates a natural principal-agent problem between medical school and engineering college. The key to a partnership is the recognition of mutual benefit while addressing inequalities and other problems that undermine joint ventures (Eddy, 2010). Even small issues can create big hurdles.

Several interviewees described the different cultural and organizational structures that exist in university departments and medical schools. Elaborating on navigating a joint grant, InterviewB pointed to the different goals of Clemson and The Medical College of South Carolina. She elaborated on the day-to-day differences by explaining, "Constraints of a medical school are very different from *engineering and science schools. The easiest thing to point to is tenure. Tenure track faculty in an engineering school have salary guaranteed for nine months to teach classes, and then they just have to cover the summer. At medical schools, they can only do research to cover their salary."*

InterviewF, a former faculty member in the VT College of Engineering, described the initial approval process for the inter-university relationship saying, "*We had to get approval between the states, you know, as a public and a private…Getting both institutions on the diploma was a piece of cake compared to [creating] a new logo."*

Reducing unneeded obstacles and planning collaborative institutions results in stronger ties and lower costs. For policymakers interested in future inter-university partnerships, the following recommendations should be considered in planning.

4.6 Policy Recommendations for future inter-university partnerships

Because some type of inter-university partnership was present in each heterogeneous path examined herein, this research can make recommendations for policymakers interested in future inter-university partnerships in high-tech, interdisciplinary disciplines. Table 6 displays samples of first-order coding and the aggregation of second-order coding into categories based on common themes in the data. Three areas have sufficient similarities across cases and can thus be related to a successful inter-university partnership: leadership, capacity, and processes.

Intrapreneurship literature tells us that supportive leadership is critical to the success of any new venture. Based on these cases, the following leadership characteristics are identified as important to the success of an inter-university partnership: buy-in, generating external and internal support, alignment of individual rewards and goals, navigating organizational hurdles, enabling intrapreneurs, and performing ongoing maintenance. Multiple leaders may fill these leadership roles on different levels in the university.

Interdisciplinary research in translational academic fields like biomedical engineering attempts to increase the university's capacity to solve complex problems. Additional human capital is as important as access to physical capital when expanding capacity in interdisciplinary research. Based on the cases examined herein, four dimensions of increasing capacity are identified in the process of obtaining medical facilities and researchers: acting on visionary ideas, combining human capital from different disciplines, shared access to constrained resources, and organic growth that is research-faculty initiated.

Conflicting interests of the partners, poor communication, and lack of clearly defined objectives and responsibilities are seen as the main reasons for alliance failure (Dodouya, 2009). Successful partnerships include active teamwork, joint problem-solving, open information sharing, intercultural understanding, continuous improvement, involvement, and clearly defined and agreed-upon goals (Serrano, 2018; Dodouya, 2009). The day-to-day operations of the partnership matter. Data collected in the case studies lists the following processes that positively support inter-university partnerships: Addressing retention, promotion, and tenure differences, proactively planning to address future problems, encouraging interaction between faculty researchers and students, and funding through a single cost center to make collaboration easier.

4.7 Limitations and Discussion

Case studies focus on explaining how and why an event happens by obtaining data through direct observation, interviews, or document analysis (Serrano, 2018). Targeted interviews and online data gathering allow the researcher to go deeper than a survey, dependent on responder knowledge and willingness to participate (Clausen et al., 2012). This multiple case study seeks to illuminate the motives and processes taken by intrapreneurs in a strategically entrepreneurial university setting. Examining successful intrapreneurs and new ventures in context helps us understand entrepreneurial organizations (Antonic and Hisrich, 2003). Prior quantitative research showed that inter-university collaboration and partnerships affect the quality of research and development, on average.

The generalizability of results from this case study is limited due to several factors. First, the process examined in the paper specifically refers to how universities obtain needed resources once a decision has been made to expand in an interdisciplinary, highly technical field like biomedical engineering. Second, only four cases were examined. A higher number of cases with more interviews would strengthen the internal validity of the research. I believe the total number of inter-university partnerships in BME is less than 15, and even fewer are old enough to warrant study, but more interviews would still be beneficial. Finally, the case study included only existing inter-university partnerships. The addition of at least one partnership that failed is needed for comparison. Given these limitations, care should be taken in using the results out of context, and the findings of the case study should not be generalized for all inter-university partnerships.

Literature tells us that new fields challenge the authority of established centers of power in academia (Braun, 2011). With expanded research to include earlier entrants to the field and failed partnerships, I would expect to find more evidence of pushback from existing faculty in engineering departments that want to expand into the field of BME by collaborating with medical researchers.

It is also important to note that not all biomedical engineering research takes place in the biomedical engineering department within the university. The interdisciplinary nature of the discipline means researchers from multiple areas may be involved. Further, universities may strategically keep established research areas in their original home departments. Because faculty are often free to follow their interests, university funders and administration build on diverse capacities creating a very complex structure of initiatives, centers, collaboratives, and departments. For example, Clemson started the School of Health Research in 2013, and NC State has a Comparative Medicine Institute with 23 departments from six colleges and four universities collaborating under one banner.

This paper exploits heterogeneous paths through the make-buy-partner process of obtaining medical facilities and researcher knowledge to put BME inter-university partnerships in context and provide takeaways to support interdisciplinary, highly technical partnerships in the future. Prior quantitative research showed that inter-university curricular collaborations in biomedical engineering positively affected the quality of research in the academic field of biomedical engineering. The aim of this work is to contribute to science and higher education policy and literature by examining the motives of intrapreneurs acting within strategically entrepreneurial universities.

A common make-buy-partner decision-making process was identified for universities that choose to obtain a needed resource. Before the make-buy-partner process begins, global external factors motivate universities with path-dependent capacities to expand. After choosing to do so by obtaining medical facilities and researcher knowledge, universities strategically navigate a heterogeneous path through the common make-buy-partner process. University intrapreneurs are instrumental in forming inter-university partnerships, and former faculty collaborations seem to be an important predictor of increased research collaboration between the two partners. This is an interesting initial result that requires more investigation to confirm.

Common characteristics of successful inter-university partnerships are also presented for policymakers and university leaders who are interested in future inter-university partnerships. Similarities across data obtained from different sources support recommendations in three areas: leadership, capacity building, and supportive processes. Observational data collected herein confirms that partnerships benefit from motivated intrapreneurs and visionary leaders who must provide continuous oversight. Resources required are not inconsequential, but the benefits of an inter-university partnership likely impact the university's future capacity to education and produce new knowledge.

Tables and Figures

Table 1

Where does a university fall in the entrepeneurial spectrum?

	Public Entrepreneurship	**Academic Entrepreneurship**	**Strategic Entrepreneurship**
Output Goals	Creating value for citizens by bringing together unique combinations of public and or private resources to exploit social opportunities (Morris and Jones, 1999)	Translation of new knowledge to create commercial and social value with focus on university-industry collaboration. (Burkholder and Hulsink, 2022; Siegel and Wright, 2015; Beckman and Cherwitz, 2009)	Growth that creates value for stakeholders by identifying and exploiting new opportunities to sustain a competitive advantage in a dynamic and competitive environment. (Hitt, Ireland, Trahms, 2011; Schendel and Hill, 2007)
Organization objectives	Diversity and multiplicity of objectives; greater conflict among objective (Kearney, Hisrich and Roche, 2009)	Translation of research to economic and social contributions outside university. (Siegel and wright, 2015)	Supporting the twin needs of exploration and exploitation within organization. (Benner & Tushman, 2003, Hitt, Ireland and Trahms 2011)
Decision making authority and focus in the organization	Authoritarian and centrally controlled. Political events may be more important than economics. Less decision making autonomy and flexibility; more concentraited on procedures and operations; subject to public scrutiny; major decisions must be transparent. (Kearney, Hisrich and Roche, 2009)	Intermediating networks driven by technology transfer including TTO, property based institutions (incubators, technology and research parks), entrepreneurship programs and centers which are often alumni supported. (Siegel and Wright, 2015; Slaughter and Rhodes, 2004)	Focus on developing and maintaining competitive advantage over time; Managers are encourged to bundle resources to enhance capabilities; interdependent decision making becomes more important as competiton reaches parity. (Hitt, Ireland and Trahms 2011)
Motivation of individual entrepreneurs & intrapreneurs	Societal benefits, non-financial gain. Lower commitment to job satisfaction (Kearney, Hisrich and Roche, 2009)	Societal, organizational and individual/industry benefits, financial and reputational, generated by commericialization of university research (Slaughter and Rhodes, 2004; Burkholder and Hulsink, 2022)	Incentivised by multiple levels of benefits: societal, organizational benefits, and individual. (Hitt, Ireland and Trahms 2011)

Table 2

Intrapreneurship dimensions applied to universities

Based on Antoncic and Hisrich's 8 Dimensions of Intrapreneurship (2003)

	Definition from Industry	Applied to the University	
New Ventures	Creation of new autonomous or semi-autonomous units	Creation of new centers, iniatives, and departments.	Examples: Joint BME department, interdisciplinary institutes and centers
New Businesses	Pursuits of and entering into new businesses related to current products or markets	Creation of external degree programs in new markets and new revenue generating programs in existing markets.	Examples: GT/Emory/PKU BME in China, corporate training programs
Product/Services innovation	Creation of new products and services	Entering new academic fields and creating new degrees in existing areas of study	Examples: Biomedical engineering, new professional graduate certificates and degrees
Process Innovativeness	Innovation in production procedures and techniques	Innovation is research methods or curriculum delivery	Examples: online education, interdisciplinary research buildings.
Self Renewal	Strategy formulation, reorganization and organizational change	Reorganizing departments, updating curriculum, changing mission or goals	Example: BEAM at VT
Risk Taking	Possibility of loss related to quickness in taking bold actions and committing resources in the pursuit of new opportunities	Possibility of loss resulting from commitment of university, college, or department resources to experimental pursuits.	Examples: Inter-university partnerships, research parks, buildings devoted to one intiative.
Proactiveness	Top management orientation for pioneering and initiative taking	Universities attempt to lead by creating and utlizing new knowledge	Examples: obtaining facilities needed for new field or expansion, adoption of new techniques in labs and clinics.
Competitive Aggresiveness	Aggressive posturing towards competitors	Competition exists on several levels: attracting faculty, students, and research funding; can be global, national or regional.	Example: Accreditation activities, grant proposals, highlighting star research and awards.

Table 3

Summary Statistics and Characteristics of University Cases[1]

	Georgia Tech	**NC State**	**VA Tech**	**Clemson**
Location	Atlanta, GA	Raleigh, NC	Blacksberg, VA	Clemson, SC
Governance	Public	Public	Public	Public
Accredited Engineering Programs (2023)	14	19	15	12
Undergraduate BME / BioE (year accredited)	2003	2002	n/a	2009
University Medical Facilities (Prior to Process)	none	College of Veterinary medicine	College of Veterinary medicine Osteopathic med school	none
Research Expenditure (2021)	$1,114,481,000	$547,118,000	$542,045,000	$237,485,000
BME Publications (1980-2020)	3832	2193	1776	967
Rank Graduate Engineering School (USNews 2023)	5	25	30	77
University Rank (US News 2023)	33	60	47	86
Inter-University Partner for BME	Emory (Atlanta, GA)	UNC Chapel Hill (Chapel Hill, NC)	Wake Forest (Winston-Salem, NC)	Medical Univ of SC (Charleston, SC)
BME Publications with Partner (%)	1120 (29.2%)	431 (19.7%)	192 (10.8%)	108 (11.2%)
Distance to Partner (time)	5.4 miles (20 mins)	31 miles (40 mins)	197 miles (3 hr 43 mins)	240 miles (3 hr 37 mins)
Joint BME Research Focus Areas (2023)	Biomaterials Bio-robotics Cancer technologies Cardiovascular engineering Imaging Immunoengineering Informatics Neuroengineering	Imaging Microdevices Pharmacoengineering Rehabilitation engineering Regenerative medicine	Biomaterials Biomechanics Cardiovascular engineering Imaging Nanobioengineering Neuroengineering Tissue engineering Translational cancer	Biomaterials Bioinstrumentation Biomechanics Cellular and biomolectular engineering Regenerative medicine

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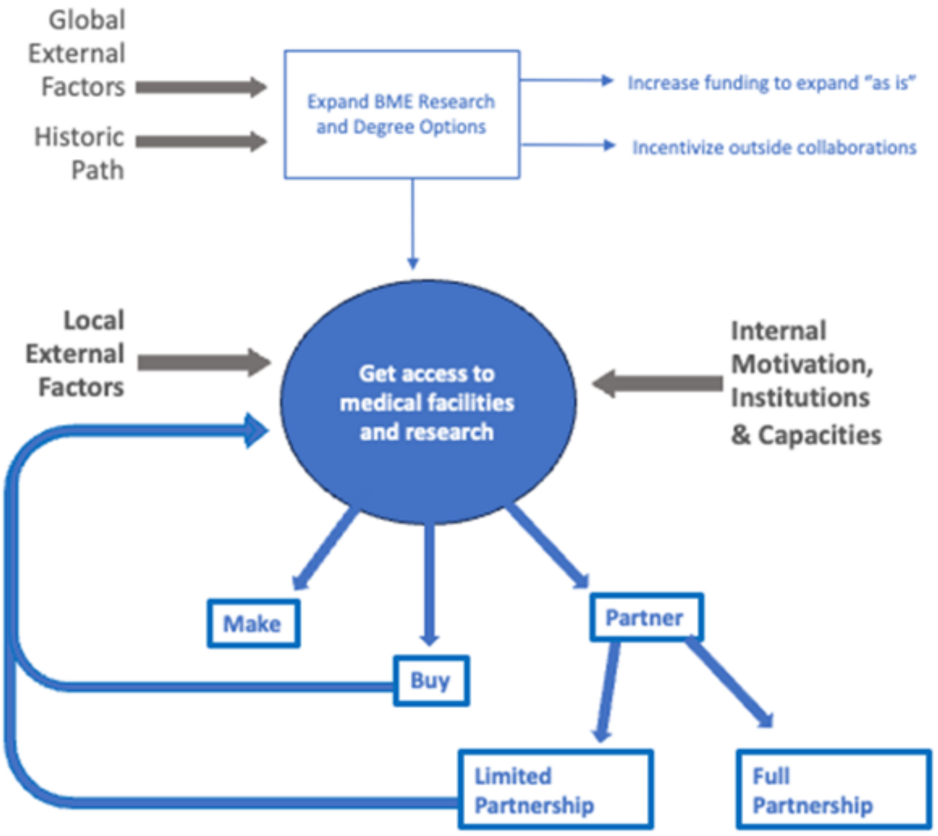
[1] Sources: https://bme.gatech.edu/bme/, https://bme.unc.edu/, https://beam.vt.edu/graduate/biomedical.html, https://www.clemson.edu/cecas/departments/bioe/, https://www.usnews.com/best-graduate-schools/top-engineering-schools, https://www.usnews.com/best-colleges, https://ncses.nsf.gov/surveys/higher-education-research-development/2021#data, https://www.google.com/maps/, https://www.lens.org/, https://amspub.abet.org/aps/name-search?searchType=institution.

Figure 1

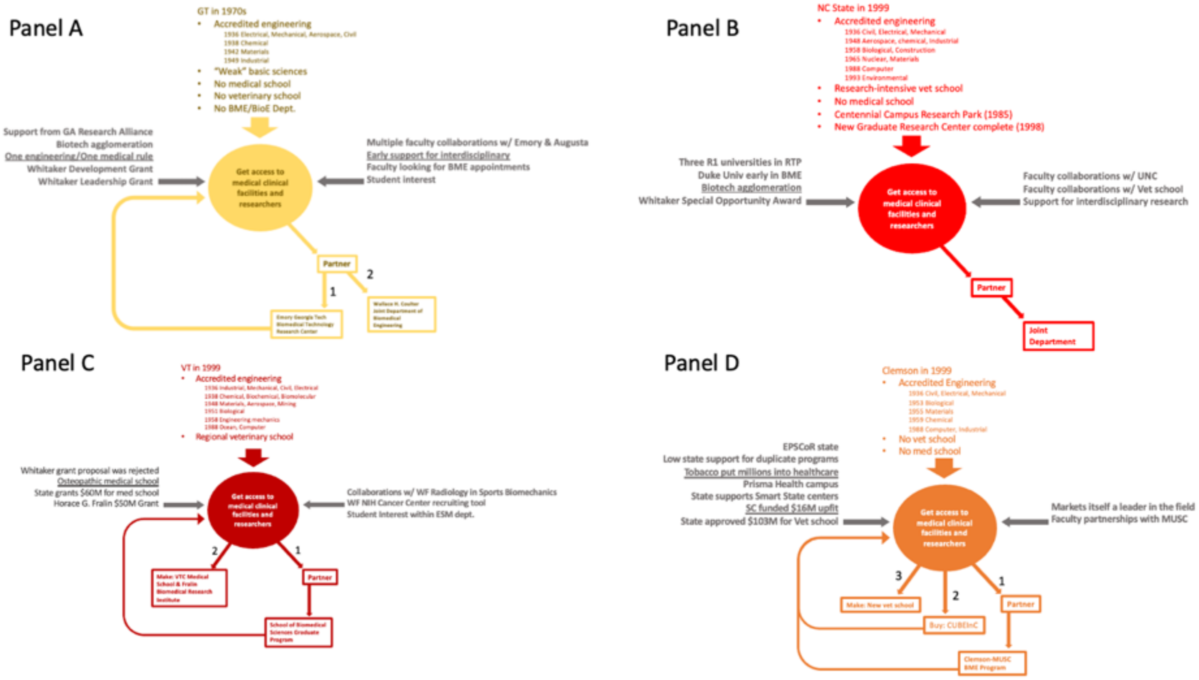
Make-Buy-Partner Process Diagram



Building on Hitt et al.'s (2011) Input-Process-Output model of strategic entrepreneurship, this diagram explains the process of resource orchestration. Prior to the process, global external factors led path-dependent universities to expand their BME programs by obtaining medical facilities and researchers. Inputs to the process include local external factors and internal motivations, institutions, and capacities. Each university followed a heterogeneous path through this make-buy-partner process; all chose to partner at some point during the expansion.

Figure 2

Process Diagrams for Individual Universities



Panels A-D show each university's paths through the make-buy-partner process to obtain medical facilities and researchers. The university enters the process with unique capabilities. With the exception of NC State, each university went through the process multiple times. Local external factors and individual motivations play a role in the path taken. Outcomes from multiple paths in the process are numbered. A line divides changes in external and internal factors for each pass through the process, if applicable.

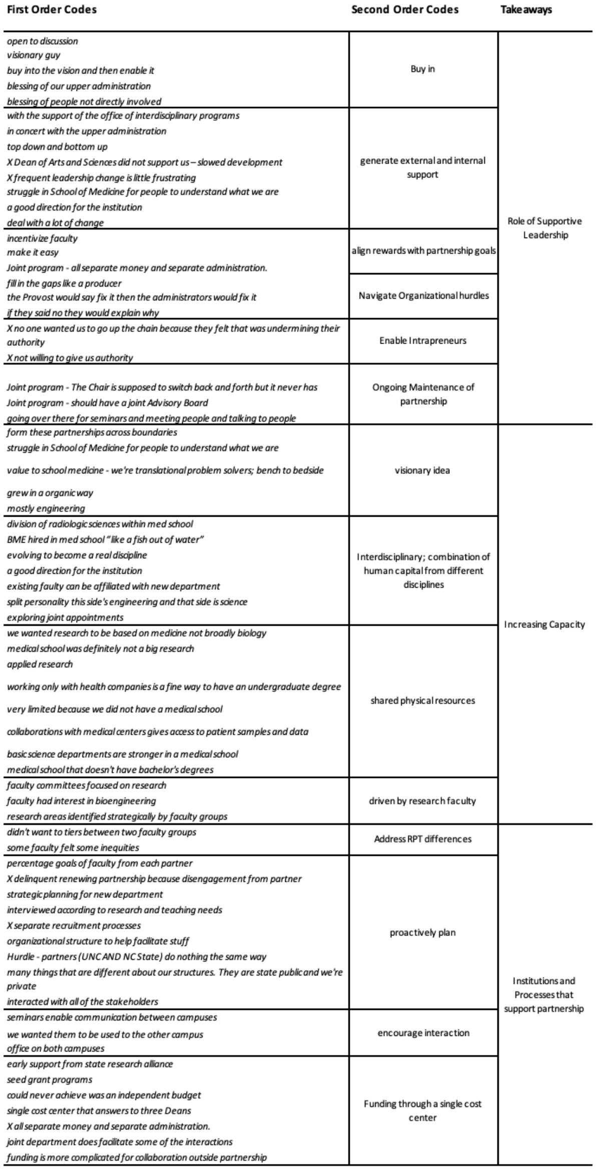
Table 5

Observed Determinants of the Make-Buy-Partner Process

Make	**Buy**	**Partner**
Major state funding support	Uncertainty	Prior Faculty Collaborations
Political support	Limited state support	Persistent Faculty Intrapreneurs
Aligns with university goals	Strong regional health system	Regional peer with complementary resources
	Strong industry partner	Graduate curricluar expansion
	Undergraduate expansion	Major grants supporting new discipline
	Short term commitment	Accreditation aspirations

Limited	**Full**
Uncertainty	Focus on research capacity
Governance barriers	Stakeholders can easily access both campuses
Curricular focus	Long run focus
Funding focus	

Table 6 Sample of First and Second-Order Coding Leading to Policy Recommendations



First Order Codes	**Second Order Codes**	**Takeaways**
open to discussion *visionary guy* *buy into the vision and then enable it* *blessing of our upper administration* *blessing of people not directly involved*	Buy in	Role of Supportive Leadership
with the support of the office of interdisciplinary programs *in concert with the upper administration* *top down and bottom up* *X Dean of Arts and Sciences did not support us – slowed development* *X frequent leadership change is little frustrating* *struggle in School of Medicine for people to understand what we are* *a good direction for the institution* *deal with a lot of change*	generate external and internal support	
incentivize faculty *make it easy* *Joint program - all separate money and separate administration.*	align rewards with partnership goals	
fill in the gaps like a producer *the Provost would say fix it then the administrators would fix it* *if they said no they would explain why*	Navigate Organizational hurdles	
X no one wanted us to go up the chain because they felt that was undermining their authority *X not willing to give us authority*	Enable Intrapreneurs	
Joint program - The Chair is supposed to switch back and forth but it never has *Joint program - should have a joint Advisory Board* *going over there for seminars and meeting people and talking to people*	Ongoing Maintenance of partnership	
form these partnerships across boundaries *struggle in School of Medicine for people to understand what we are* *value to school medicine - we're translational problem solvers; bench to bedside* *grew in a organic way* *mostly engineering*	visionary idea	Increasing Capacity
division of radiologic sciences within med school *BME hired in med school "like a fish out of water"* *evolving to become a real discipline* *a good direction for the institution* *existing faulty can be affiliated with new department* *split personality this side's engineering and that side is science* *exploring joint appointments*	Interdisciplinary; combination of human capital from different disciplines	
we wanted research to be based on medicine not broadly biology *medical school was definitely not a big research* *applied research* *working only with health companies is a fine way to have an undergraduate degree* *very limited because we did not have a medical school* *collaborations with medical centers gives access to patient samples and data* *basic science departments are stronger in a medical school* *medical school that doesn't have bachelor's degrees*	shared physical resources	
faculty committees focused on research *faculty had interest in bioengineering* *research areas identified strategically by faculty groups*	driven by research faculty	
didn't want to tiers between two faculty groups *some faculty felt some inequities*	Address RPT differences	Institutions and Processes that support partnership
percentage goals of faculty from each partner *X delinquent renewing partnership because disengagement from partner* *strategic planning for new department* *interviewed according to research and teaching needs* *X separate recruitment processes* *organizational structure to help facilitate stuff* *Hurdle - partners (UNC AND NC State) do nothing the same way* *many things that are different about our structures. They are state public and we're private* *interacted with all of the stakeholders*	proactively plan	
seminars enable communication between campuses *we wanted them to be used to the other campus* *office on both campuses*	encourage interaction	
early support from state research alliance *seed grant programs* *could never achieve was an independent budget* *single cost center that answers to three Deans* *X all separate money and separate administration.* *joint department does facilitate some of the interactions* *funding is more complicated for collaboration outside partnership*	Funding through a single cost center	

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CHAPTER FIVE: CONCLUSIONS AND POLICY RECOMMENDATIONS

5.1 Introduction

This dissertation contributes to science policy and innovation works of literature surrounding universities. The dynamics of competition and collaboration among universities have long been informally recognized, even in the absence of extensive empirical research on the subject. Results herein show the effects of these interactions are important to the industry and economy of the regions surrounding the universities, as well as the output and capacity of the organization itself. The interdisciplinary area of biomedical engineering is used to motivate the research questions in each of the three essays included.

5.2 University Signaling: Factors Leading to Accreditation in a New Scientific Field

Chapter Two of this study delves into the diffusion of an emerging academic discipline, namely biomedical engineering by identifying characteristics that increase the likelihood of accreditation, which is broadly understood to be a signal of quality for academic programs. The model reveals that reputation, capacity, and proximity variables significantly influence the likelihood of receiving accreditation for a biomedical engineering program in a given year. The significance of proximate universities muddies the interpretation and value of the signal. The event history model employed also illuminates the diffusion and establishment of an emerging interdisciplinary field within a region. Universities with well-established reputations and robust academic capacities extend their influence on institutions of comparatively lesser prestige. Furthermore, diffusion patterns occurring within geographically proximate universities, elucidate the ways in which knowledge and expertise disseminate.

The significance of covariables connected to proximate universities illustrates university competition. If funding policy and industry are to place value on program accreditation as a signal of quality, more transparency should be a goal for policymakers. This would also be of value to students, particularly in emerging academic areas, because misleading ways of showcasing program accreditation by universities also reduces the value of the signal.

5.3 Does Inter-university Curricular Collaboration Produce Quality Research Results?

Joint departments and programs illustrate inter-universities collaboration. Chapter Three explores the phenomenon of curricular collaboration (subsequently renamed as inter-university partnerships in Chapter Four) and unearths a compelling correlation between such collaborative efforts and the enhancement of research quality. This connection underscores the critical role of cooperative initiatives in elevating the academic landscape.

The cost and benefits of university organization-level collaboration for research or curricular purposes differ from individual faculty collaboration. The model shows that inter-university curricular collaborations result in higher-quality research as measured by patent citations. The increase in quality from curricular collaborations rivals that of university-industry collaborations. Results could be extended to other highly technical interdisciplinary academic fields in the future.

Policymakers interested in technology transfer and spillover from university R&D should incentivize curricular collaborations where it makes sense. Future research, beyond university-industry alliances, should explore the social capital created by inter-university collaboration.

5.4 Inter-university Partnerships: The Intrapreneur's Path in a University's Make-Buy-Partner Process

In Chapter Four, the discussion centers on the contention that inter-university partnerships, particularly those that evolve organically from individual research collaborations, exhibit superior strength and sustainability, particularly when established among universities situated in close geographic proximity. Furthermore, it is argued that these partnerships should be initiated by faculty and researchers rather than solely by institutional administration, thereby aiming to curtail the financial burdens associated with collaborative endeavors.

The essay uses qualitative data for context and argues university partnerships resulting in joint programs or departments are not simply a make-or-buy proposition that arises due to complementary resources held by two organizations. They start with individual research collaborations, followed by faculty serving as intrapreneurs who create and promote organization-level partnerships. The administrative role is that of support and promotion.

Policymakers interested in enhancing innovative ecosystems through inter-university collaborations should focus on reducing the cost of partnering across organizational boundaries while promoting boundary-spanning research of faculty acting as intrapreneurs. Administration must remove barriers to partnerships to maximize their potential, increase social value in an ecosystem, and enhance the capacity for future research and curricula for both universities involved.

5.5 Plans for Future Research

Avenues for future research exploring university interactions are extensive and poised to gain significance as faculty become increasingly relied upon to address progressively intricate interdisciplinary inquiries while the marketplace for higher education continues to evolve. Continued exploration of existing and new inter-university partnerships is warranted to determine what characteristics might lead to greater benefits from collaboration and whether it matters what facilities existed before the collaboration. More expansive data sets and a larger interview pool would strengthen the validity and generalizability of results on this initial model described in this dissertation. Further research worth exploring would characterize universities as substitutes or complements within a region. Additional research could explore the regional effects, including inter-university and university-industry collaborations, connected to new interdisciplinary research buildings on campus.

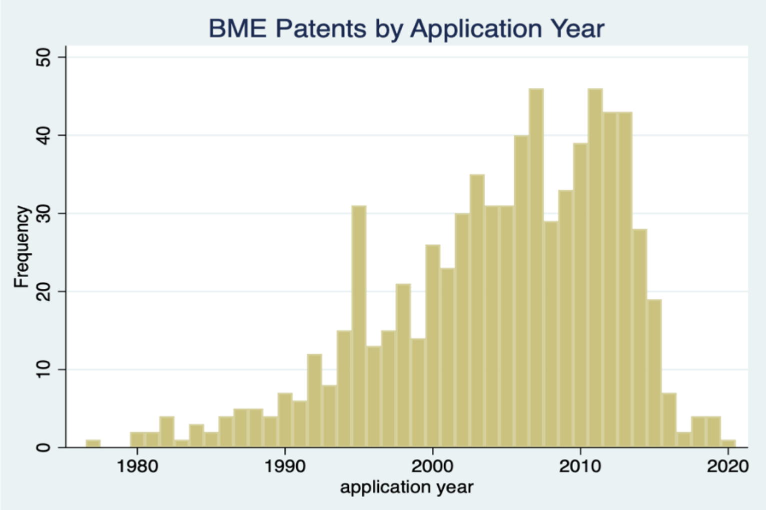
In summary, this dissertation endeavors to contribute to the academic discourse by offering insights into the multifaceted relationships between universities, emphasizing their competitive and collaborative dimensions, and discerning the effects of such interactions on knowledge diffusion, research quality, and the sustainable development of inter-university partnerships. The overall results make a significant contribution to the academic fields of science policy and innovation by shedding light on the dynamics of inter-university collaboration and competition. For scholars seeking to explore innovative ecosystems or regional economies, it is imperative to incorporate the intricate nuances of university interactions. These interactions encompass a spectrum of collaborative and competitive relationships, challenging any notion that universities are homogeneous entities coexisting within these environments.

APPENDIX 2A
Multilevel Logistic Event History Model Results

	Model 1 Capacity	**Model 2** Capacity Reputation	**Model 3** Capacity Reputation Proximity
Aspirant Cohort		2.694*	3.145*
		(1.14)	(1.48)
Current Cohort		1.416	1.534
		(0.52)	(0.62)
Rated	3.212*	4.432**	
		(1.49)	(2.32)
Nearby BME			5.792***
			(2.70)
NIH Funding Trend	4.611***	3.373***	3.501***
	(1.03)	(0.85)	(.95)
Accred. Programs	1.674***	1.568***	1.785***
Count	(0.16)	(0.149)	(.19)
R1 or R2	14.008***	8.252***	11.541***
	(6.87)	(4.38)	(6.94)
MED & ENG	16.099**	17.835*	45.442**
	(18.21)	(20.63)	(66.21)
HBCU	0.059	0.065	0.021
	(0.10)	(0.11)	(0.04)
Firms Ratio	5.104**	3.532	1.993
	(3.46)	(2.45)	(1.61)
Census District (Pacific=0)			
Mountain	0.198	0.311	0.352
	(0.19)	(0.29)	(0.39)
West N. Central	0.617	0.615	0.714
	(0.58)	(0.59)	(0.81)
East N. Central	5.009*	6.053*	6.284*
	(3.65)	(4.58)	(5.34)
West S. Central	2.723	3.058	3.681
	(2.23)	(2.54)	(3.64)
East S. Central	1.054	1.527	2.089
	(1.02)	(1.51)	(2.45)
South Atlantic	3.678	4.065	4.364
	(2.76)	(3.14)	(4.02)
Mid Atlantic	7.769**	7.739**	6.884*
	(5.73)	(5.86)	(6.18)
New England	4.852	5.201	4.154
	(4.02)	(4.41)	(4.12)
var(_cons[~)	7.505	579.7	12.819
(2.32)	(2.81)	(3.49)	
N	22786	22786	22786
Log Likelihood	-627.992	-621.640	-614.356
AIC	1287.983	1281.281	**1268.713**
BIC	**1416.526**	1433.925	1429.391
Df	16	19	20

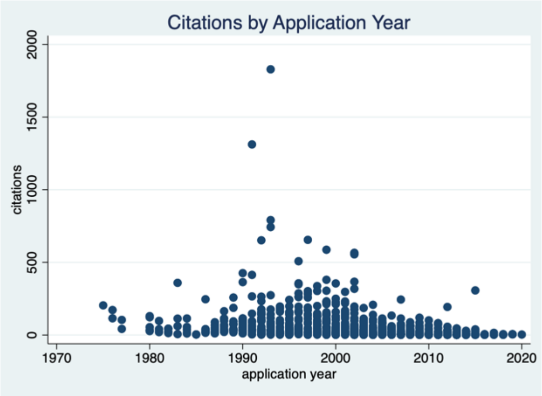
Odds Ratios; t statistics in parentheses
* p<0.05, ** p<0.01, *** p<0.001

Appendix 3A Biomedical Patents by Application Year

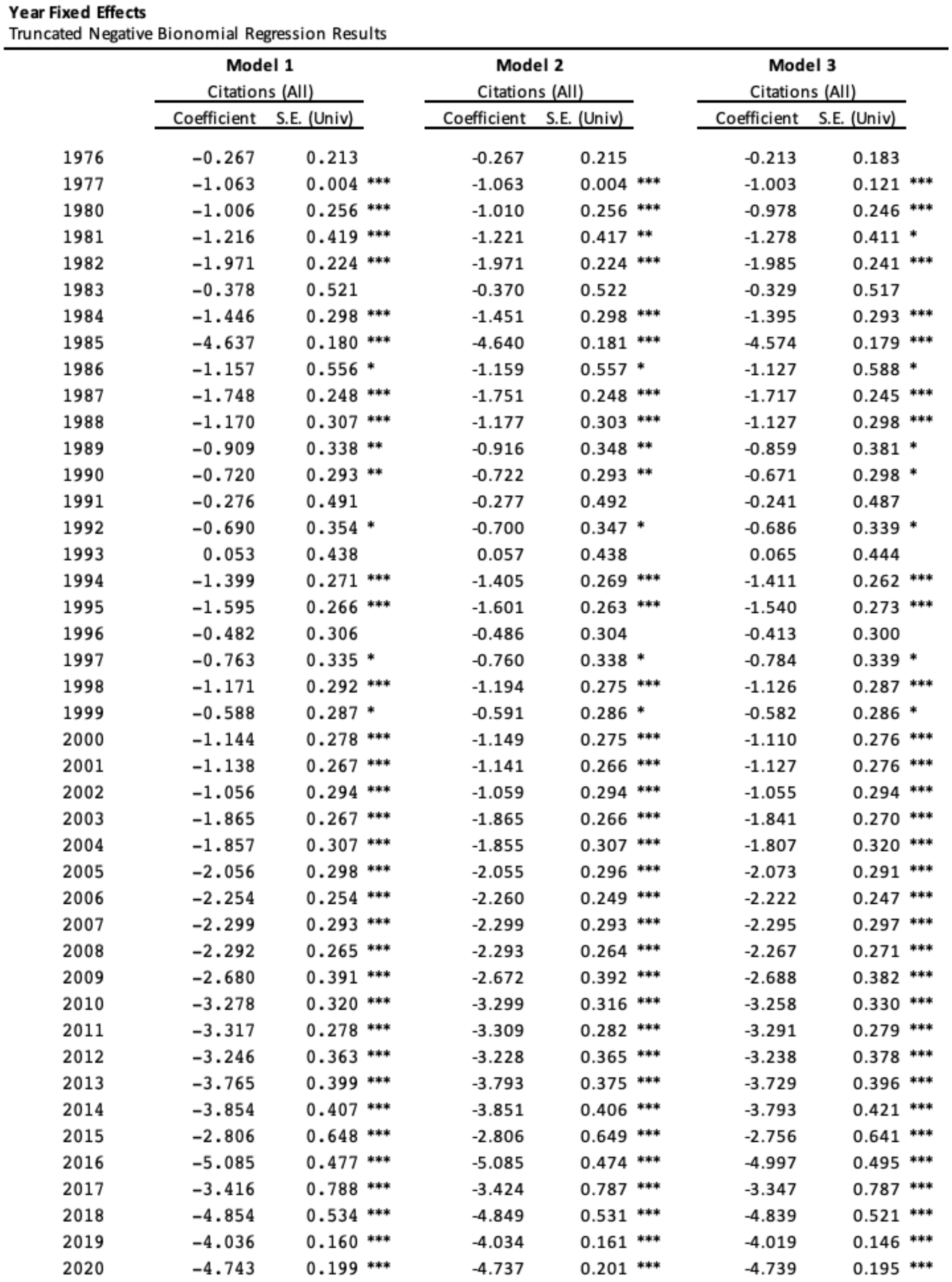


All patents in the data set have a grant date on or before 2021.
The time between the application and grant date varies and explains the decline in patent applications was seen in the graph around 2015.

APPENDIX 3B Patent Citations by Application Year of Cited Patent



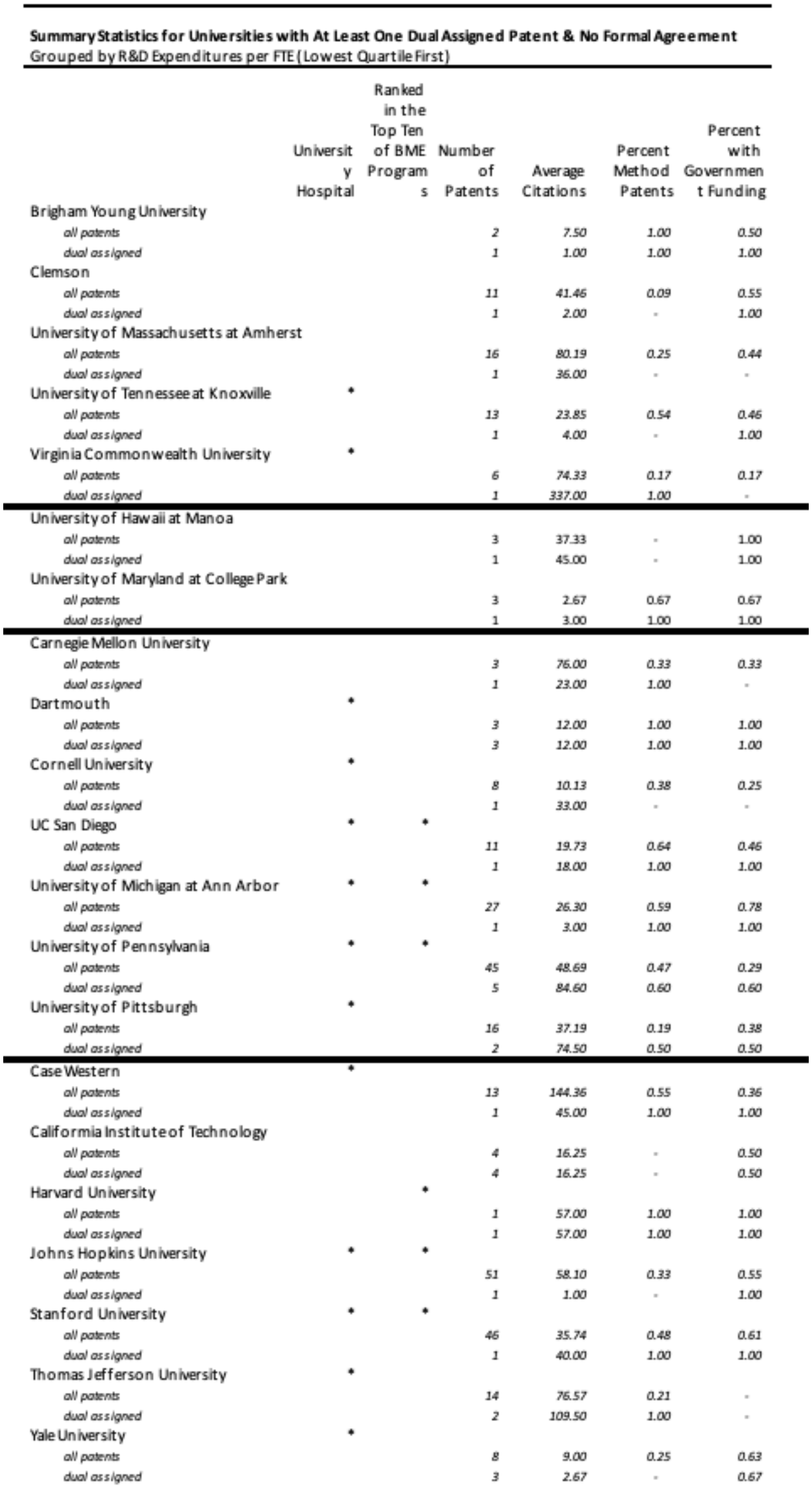
APPENDIX 3C Application Year Fixed Effects



Year Fixed Effects
Truncated Negative Bionomial Regression Results

	Model 1		Model 2		Model 3	
	Citations (All)		Citations (All)		Citations (All)	
	Coefficient	S.E. (Univ)	Coefficient	S.E. (Univ)	Coefficient	S.E. (Univ)
1976	−0.267	0.213	-0.267	0.215	-0.213	0.183
1977	−1.063	0.004 ***	-1.063	0.004 ***	-1.003	0.121 ***
1980	−1.006	0.256 ***	-1.010	0.256 ***	-0.978	0.246 ***
1981	−1.216	0.419 ***	-1.221	0.417 **	-1.278	0.411 *
1982	−1.971	0.224 ***	-1.971	0.224 ***	-1.985	0.241 ***
1983	−0.378	0.521	-0.370	0.522	-0.329	0.517
1984	−1.446	0.298 ***	-1.451	0.298 ***	-1.395	0.293 ***
1985	−4.637	0.180 ***	-4.640	0.181 ***	-4.574	0.179 ***
1986	−1.157	0.556 *	-1.159	0.557 *	-1.127	0.588 *
1987	−1.748	0.248 ***	-1.751	0.248 ***	-1.717	0.245 ***
1988	−1.170	0.307 ***	-1.177	0.303 ***	-1.127	0.298 ***
1989	−0.909	0.338 **	-0.916	0.348 **	-0.859	0.381 *
1990	−0.720	0.293 **	-0.722	0.293 **	-0.671	0.298 *
1991	−0.276	0.491	-0.277	0.492	-0.241	0.487
1992	−0.690	0.354 *	-0.700	0.347 *	-0.686	0.339 *
1993	0.053	0.438	0.057	0.438	0.065	0.444
1994	−1.399	0.271 ***	-1.405	0.269 ***	-1.411	0.262 ***
1995	−1.595	0.266 ***	-1.601	0.263 ***	-1.540	0.273 ***
1996	−0.482	0.306	-0.486	0.304	-0.413	0.300
1997	−0.763	0.335 *	-0.760	0.338 *	-0.784	0.339 *
1998	−1.171	0.292 ***	-1.194	0.275 ***	-1.126	0.287 ***
1999	−0.588	0.287 *	-0.591	0.286 *	-0.582	0.286 *
2000	−1.144	0.278 ***	-1.149	0.275 ***	-1.110	0.276 ***
2001	−1.138	0.267 ***	-1.141	0.266 ***	-1.127	0.276 ***
2002	−1.056	0.294 ***	-1.059	0.294 ***	-1.055	0.294 ***
2003	−1.865	0.267 ***	-1.865	0.266 ***	-1.841	0.270 ***
2004	−1.857	0.307 ***	-1.855	0.307 ***	-1.807	0.320 ***
2005	−2.056	0.298 ***	-2.055	0.296 ***	-2.073	0.291 ***
2006	−2.254	0.254 ***	-2.260	0.249 ***	-2.222	0.247 ***
2007	−2.299	0.293 ***	-2.299	0.293 ***	-2.295	0.297 ***
2008	−2.292	0.265 ***	-2.293	0.264 ***	-2.267	0.271 ***
2009	−2.680	0.391 ***	-2.672	0.392 ***	-2.688	0.382 ***
2010	−3.278	0.320 ***	-3.299	0.316 ***	-3.258	0.330 ***
2011	−3.317	0.278 ***	-3.309	0.282 ***	-3.291	0.279 ***
2012	−3.246	0.363 ***	-3.228	0.365 ***	-3.238	0.378 ***
2013	−3.765	0.399 ***	-3.793	0.375 ***	-3.729	0.396 ***
2014	−3.854	0.407 ***	-3.851	0.406 ***	-3.793	0.421 ***
2015	−2.806	0.648 ***	-2.806	0.649 ***	-2.756	0.641 ***
2016	−5.085	0.477 ***	-5.085	0.474 ***	-4.997	0.495 ***
2017	−3.416	0.788 ***	-3.424	0.787 ***	-3.347	0.787 ***
2018	−4.854	0.534 ***	-4.849	0.531 ***	-4.839	0.521 ***
2019	−4.036	0.160 ***	-4.034	0.161 ***	-4.019	0.146 ***
2020	−4.743	0.199 ***	-4.737	0.201 ***	-4.739	0.195 ***

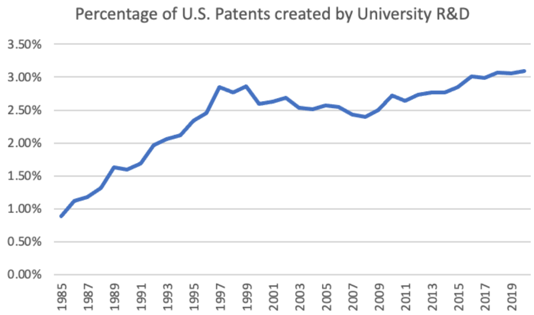
APPENDIX 3D Summary Statistics for Universities with Dual Assigned Patent(s) and No Formal Agreement



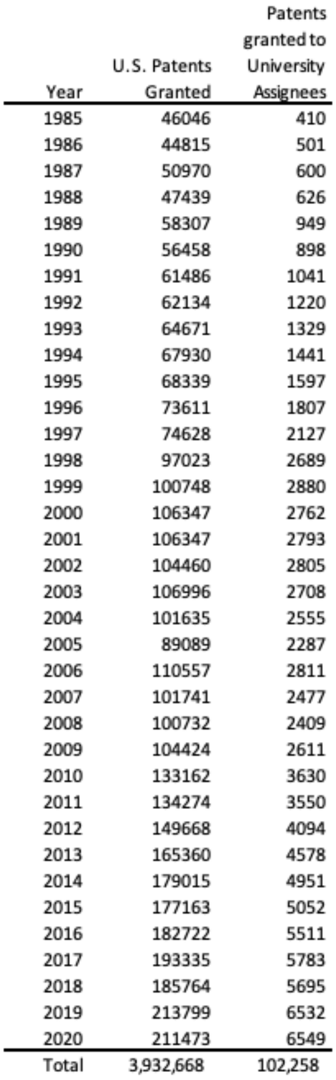
Summary Statistics for Universities with At Least One Dual Assigned Patent & No Formal Agreement
Grouped by R&D Expenditures per FTE (Lowest Quartile First)

	University Hospital	Ranked in the Top Ten of BME Programs	Number of Patents	Average Citations	Percent Method Patents	Percent with Government Funding
Brigham Young University						
all patents			*2*	*7.50*	*1.00*	*0.50*
dual assigned			*1*	*1.00*	*1.00*	*1.00*
Clemson						
all patents			*11*	*41.46*	*0.09*	*0.55*
dual assigned			*1*	*2.00*	-	*1.00*
University of Massachusetts at Amherst						
all patents			*16*	*80.19*	*0.25*	*0.44*
dual assigned			*1*	*36.00*	-	-
University of Tennessee at Knoxville	•					
all patents			*13*	*23.85*	*0.54*	*0.46*
dual assigned			*1*	*4.00*	-	*1.00*
Virginia Commonwealth University	•					
all patents			*6*	*74.33*	*0.17*	*0.17*
dual assigned			*1*	*337.00*	*1.00*	-
University of Hawaii at Manoa						
all patents			3	37.33	-	1.00
dual assigned			1	45.00	-	1.00
University of Maryland at College Park						
all patents			3	2.67	0.67	0.67
dual assigned			1	3.00	1.00	1.00
Carnegie Mellon University						
all patents			*3*	*76.00*	*0.33*	*0.33*
dual assigned			*1*	*23.00*	*1.00*	-
Dartmouth	•					
all patents			*3*	*12.00*	*1.00*	*1.00*
dual assigned			*3*	*12.00*	*1.00*	*1.00*
Cornell University	•					
all patents			*8*	*10.13*	*0.38*	*0.25*
dual assigned			*1*	*33.00*	-	-
UC San Diego	•	•				
all patents			*11*	*19.73*	*0.64*	*0.46*
dual assigned			*1*	*18.00*	*1.00*	*1.00*
University of Michigan at Ann Arbor	•	•				
all patents			*27*	*26.30*	*0.59*	*0.78*
dual assigned			*1*	*3.00*	*1.00*	*1.00*
University of Pennsylvania	•	•				
all patents			*45*	*48.69*	*0.47*	*0.29*
dual assigned			*5*	*84.60*	*0.60*	*0.60*
University of Pittsburgh	•					
all patents			*16*	*37.19*	*0.19*	*0.38*
dual assigned			*2*	*74.50*	*0.50*	*0.50*
Case Western	•					
all patents			*13*	*144.36*	*0.55*	*0.36*
dual assigned			*1*	*45.00*	*1.00*	*1.00*
Califormia Institute of Technology						
all patents			*4*	*16.25*	-	*0.50*
dual assigned			*4*	*16.25*	-	*0.50*
Harvard University		•				
all patents			*1*	*57.00*	*1.00*	*1.00*
dual assigned			*1*	*57.00*	*1.00*	*1.00*
Johns Hopkins University	•	•				
all patents			*51*	*58.10*	*0.33*	*0.55*
dual assigned			*1*	*1.00*	-	*1.00*
Stanford University	•	•				
all patents			*46*	*35.74*	*0.48*	*0.61*
dual assigned			*1*	*40.00*	*1.00*	*1.00*
Thomas Jefferson University	•					
all patents			*14*	*76.57*	*0.21*	-
dual assigned			*2*	*109.50*	*1.00*	-
Yale University	•					
all patents			*8*	*9.00*	*0.25*	*0.63*
dual assigned			*3*	*2.67*	-	*0.67*

APPENDIX 3E Percentage of Patents; Total and University Assignees, 1985-2020



APPENDIX 3F US Patents Grants 1985-2020



Year	U.S. Patents Granted	Patents granted to University Assignees
1985	46046	410
1986	44815	501
1987	50970	600
1988	47439	626
1989	58307	949
1990	56458	898
1991	61486	1041
1992	62134	1220
1993	64671	1329
1994	67930	1441
1995	68339	1597
1996	73611	1807
1997	74628	2127
1998	97023	2689
1999	100748	2880
2000	106347	2762
2001	106347	2793
2002	104460	2805
2003	106996	2708
2004	101635	2555
2005	89089	2287
2006	110557	2811
2007	101741	2477
2008	100732	2409
2009	104424	2611
2010	133162	3630
2011	134274	3550
2012	149668	4094
2013	165360	4578
2014	179015	4951
2015	177163	5052
2016	182722	5511
2017	193335	5783
2018	185764	5695
2019	213799	6532
2020	211473	6549
Total	3,932,668	102,258

APPENDIX 4A

Interview Questions

1. What are some things you like about the joint program/department? What are some drawbacks of having a joint program/department? Have you worked in single institution BME departments? If possible, please discuss how administrative teams and university leadership support the joint department.

2. How do faculty/PIs discover what's happening in other labs or find collaborators on another campus? Are there community-building events? Are decisions about research projects internal (own defined problems) or external?

3. What do you see as the "big moments" in the development of the department's success and legitimacy? Did you witness or hear of pushback from existing departments?

4. Do you know of a departmental written history detailing how and why this collaboration started? If not, do you know someone who could speak about the initial idea? Based on your perception and knowledge of the department, arrange the following motivating reasons for a joint BME department in order of importance: Funding constraints, academic entrepreneurship, need for new knowledge, need for cross-disciplinarity (combining insights from different disciplines to produce new socially relevant knowledge), competitive edge, meet student demand, access to facilities, external pressure.

5. Which BME departments would you consider to be your institutional peers? Are you aware of any joint BME departments/programs that have failed?

6. Do you know of other research faculty, administrators, or advisory board members connected to joint Ph.D. programs who might be willing to discuss this research project?