Waterloo Bridge to 2020

Research

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UNIVERSITY OF WATERLOO

Contents

Acknowledgements

This issue paper was prepared by the Advisory Group on Waterloo's Research Landscape: Research Excellence and Crossing Disciplinary and Institutional Boundaries, one of seven groups tasked with evidence-gathering prior to development of the University of Waterloo strategic plan for 2020-2025.

What follows is a summary of current thinking drawn from the literature on the state of research in academe and of potential opportunities framed in the context of the University of Waterloo research landscape. The document is meant to stimulate discussion and facilitate the generation of ideas during the upcoming university-wide consultation that will inform the strategic plan.

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Executive summary

A number of indicators support the assertion that the University of Waterloo is highly regarded as a research institution. Moving forward into 2020 and beyond, the University must sustain and surpass this reputation in an increasingly competitive global environment. *This will require building on existing discipline-specific research excellence, fostering interdisciplinary collaboration through meaningful interactions and exchange of ideas across disciplinary boundaries, and seizing opportunities to lead in new and emerging research areas.* Issues that will need to be addressed, insights and best practices for confronting these issues, Waterloo's current research landscape, and questions for consultation with the community are delineated in this summary.

Issues and context

Enhancing cross-Faculty and within-Faculty interdisciplinary research in a highly decentralized environment whilst maintaining and building new discipline-specific research strengths.

Waterloo has major discipline-based research strengths in all its Faculties that are the foundation of its sterling research reputation. Moving forward, the University must ensure that these strengths are not only maintained, but developed anew with emphasis on retention and recruitment of excellent faculty who, through creative and impactful discipline-specific research, bring recognition and distinction to the University.

Interdisciplinary research that is cross-Faculty in nature or occurs within Faculties is also important. Some leading institutions, such as Massachusetts Institute of Technology (MIT) are combining disciplinary research strength with the flexibility to create research centres that bridge disciplinary divides. There is ample evidence that interdisciplinary research provides new opportunities for impact, broadens the relevance of research and has the potential to create new fields. This is illustrated, for example, by the evolution of quantum information and nanotechnology at Waterloo.

Moreover, academics are increasingly competing for research funding in an era of outcomes-focused research conducted by research teams, typically interdisciplinary teams that cross Faculty boundaries. Indeed, many research sponsors have moved away from requiring only individual excellence to supporting teams with multidisciplinary expertise within a strong, networked institutional environment. Yet, there are numerous barriers to pursuing interdisciplinary research. These include funding constraints, narrow definitions of merit that do not value interdisciplinary research for career development, lack of space for co-locating researchers from different Faculties to develop cross-disciplinary communities, and the perceived risk of weakening research in a given Faculty through bleeding of high profile researchers into cross-Faculty interdisciplinary initiatives. A major joint report by the Committee on Facilitating Interdisciplinary Research, the National Academies of Sciences and Engineering, and the Institute of Medicine concludes that successful institutions are likely to be those that are nimble in developing policies that mitigate barriers to cross-disciplinary research. Through such policies, opportunities to grow relationships and establish connections should be afforded to faculty interested in interdisciplinary research, enabling them to form teams and seek funding.

Interdisciplinary research within Faculties at Waterloo is alive and well, and it will be important to ensure that this continues to be encouraged and facilitated. It bears noting, though, that the

environment at Waterloo is not always conducive to grass-roots, cross-Faculty collaboration. At issue, therefore, is removing these barriers where they exist and, in so doing, more effectively enable cross-Faculty initiatives. Waterloo supports seven University Centres/Institutes conducting cross-Faculty interdisciplinary research in areas aligned with its strengths. Given its decentralized modus operandi and the new Waterloo Budget Model, however, a major challenge for Waterloo going forward will be mobilizing the resolve to permit cross-Faculty collaboration to grow to new heights, comparable to those in place in a number of other leading institutions, in order to maintain and strengthen anew global recognition as a research-intensive institution. This could include incentivizing strategic joint cross-Faculty appointments and implementing measures to more fully realize the potential of University centres and institutes as vehicles for cross-Faculty and within-Faculty interdisciplinary research.

Addressing the interface between the physical sciences/engineering and medicine, absent a Medical School

Waterloo is the only U15 institution without a medical school, yet is a tour de force at the interface between the physical sciences/engineering and medicine. Virtually all Faculties are, to a degree, engaged in research that has the potential to shape the future of medicine, and not having a medical school could well become a limitation that Waterloo will have to address. Options include creating formal institutional research agreements with teaching hospitals such as Sunnybrook Hospital and the University Health Network at the University of Toronto, as MIT has done with Harvard's teaching hospitals. Another longer-term strategy might be to pursue the establishment of a new, non-traditional medical school at Waterloo, one that has a strong technical focus underpinned by the physical sciences and engineering, yet would arguably enhance Waterloo's health-related research broadly across campus.

Increasing research funding in an era of extreme pressure on research dollars

There are more researchers, in more institutions, chasing limited research dollars than ever before. This presents a challenge for all research, whether single-disciplinary or interdisciplinary, although it appears to be more difficult to secure funding for interdisciplinary research. The 2017 review of Canada's fundamental science research, "Investing in Canada's Future: Strengthening the Foundations of Canadian Research" (commonly known, and referenced as the Naylor Report, 2017), contains recommendations for addressing the disproportionate shortage of funding for interdisciplinary research. As these seem likely to be implemented, it will be important going forward for Waterloo to be nimble in forming cross-Faculty and within-Faculty interdisciplinary teams and developing funding proposals for projects that require working at disciplinary intersections. Also important will be the provision of seed funding to support generation of preliminary data that will enhance the likelihood of securing major external funding for interdisciplinary research. Waterloo should also pursue strategies for further diversifying research funding beyond that provided by the Tri-Agencies, including targeting industry/government contracts with attendant leveraging as well as funding from foundations and non-profit organizations. In addition, as industries increasingly turn to Waterloo to increase their innovation, it will be important to ensure that they have access to expertise broadly across the University.

Recruiting and retaining excellent faculty, particularly from the four designated groups

Ultimately, excellence in research is about people. A university distinguishes itself by the caliber of its research faculty. Internationally renowned faculty have disproportionately high h-indices,

enhance the institution's ability to attract high quality graduate students, and are more likely to secure strong research funding. Faculty at the top of their game have the credentials to successfully lead new initiatives in emerging research areas, lend disproportionate credibility to interdisciplinary teams and are more likely to receive major national and international research awards. Many institutions in effect "buy CVs" to achieve reputational enhancement.

It will be important moving forward for Waterloo to be competitive in recruiting and retaining excellent faculty, embracing in the process equity, diversity and inclusivity which underpin the creation of a dynamic research environment with different perspectives, fresh ideas and new approaches (this issue is also raised in the Empowering People issues paper). Issues confronting Waterloo as it seeks to attract and retain excellent faculty include:

- Whether, and if so where, to invest more heavily in targeted hiring of research "stars".
- Provision of a welcoming, inclusive environment in which faculty have access to state-of-the art core facilities and equipment, are able to recruit high-quality graduate students, and are not unduly burdened with the administrivia of conducting research.
- Adoption of a more inclusive definition of research excellence that incorporates non-traditional measures of impact such as community engagement, impact on economic development and government policy, and entrepreneurial spinoff. Indeed, show-casing societal impact has assumed greater importance as the funding environment becomes more competitive.
- Developing more relevant merit evaluation guidelines for faculty involved in interdisciplinary research. Traditional evaluation and promotion systems tend to undervalue interdisciplinary research and need revision to include, for example, valuative recognition of teamwork. In addition, interdisciplinary hiring will likely require new administrative procedures.
- Consideration of broader implementation of differential teaching loads within departments and schools, recognizing that running a large internationally competitive research program is increasingly tantamount to a full-time job.

Questions for consultation with the community

- How important is it for Waterloo to engage more substantively in cross-Faculty interdisciplinary research? If doing so is important, how can Waterloo overcome the barriers to cross-Faculty research collaboration, and proactively foster and support it?
- Should provision of dedicated space for cross-disciplinary research collaboration be a priority for Waterloo?
- How can Waterloo more fully realize the potential of University centres and institutes as vehicles of cross-disciplinary research collaboration?
- Should Waterloo incentivize joint faculty appointments, and if so, how?
- Should Waterloo invest more heavily in targeted recruitment of senior research stars to enhance its reputation?
- How should research excellence and impact be assessed in disciplines that are not well served by bibliometics?
- Should Waterloo more broadly implement differential teaching loads within departments and schools?
- Should Waterloo pursue a specialized medical school with a strong technical bent aligned with its strengths in physical sciences/engineering?

1.Introduction

The purpose of this issue paper is to highlight current thinking on the future of University research and posit strategic research - enhancement opportunities for Waterloo with a view to catalyzing discussion in the research community that will guide development of the new strategic plan for 2020-2025.

This issue paper is part of an overall process to develop Waterloo's next Strategic Plan, 2020-2025. To begin this process, the president, provost, deans, and other members of the Executive Council identified broad themes and issues that are vital to strengthening and advancing the unique value proposition for the University of Waterloo. The themes were explored through a series of brief issue papers that will inform the strategic plan consultations. The ultimate purpose of this paper is to provide a series of questions to stimulate the consultation process.

The Executive Council and deans identified faculty and staff to participate in this initiative. Waterloo's library provided support for the literature scan, and a writer was hired to compile results and create the report. The process was facilitated by Institutional Analysis and Planning (IAP). Through a series of meetings between January and May of 2018, the group defined the issue, developed a literature search strategy, summarized the literature, provided input to the drafts, and developed the questions for the community.

During the initial meeting, research questions from university leadership were revised by the group members. Ideas of what constitutes research excellence and how this can be measured both across and within in different disciplines was shared. The idea of interdisciplinary research and the value of interdisciplinary and single discipline research was also discussed. Initial meetings of the working group established the research parameters pertaining to research excellence, impact and disciplinary boundaries, and distinguished them from issues belonging to graduate studies, internationalization and empowering people (equity, diversity and indigenous initiatives). The working group also discussed possible peer comparator institutions. More details about the methods, process and definitions of terms used in this paper can be found in Appendix A and B.

In subsequent meetings, the group elaborated on the core issues of research that needed to be covered, including measures of research excellence and collaboration. It was acknowledged that the issue paper would not be able to consider or collect data on non-traditional research impact data, or specific practices which inform internal tenure / promotion decisions. The group also discussed possible institutional peer comparators, and generated brainstormed list.

The Research Issue Paper Advisory Group also considered information collected from a variety of other sources:

- University data on research, analysed and reported by Waterloo’s Institutional Analysis and Planning unit;
- A report from InCites on Waterloo’s research output and impact using bibliometric measures produced by Waterloo’s Research and Impact Librarian;
- A report on Waterloo’s research networks on campus, as measured by data available in InCites, was produced by John McLevey from the Faculty of Environment (Appendix C), and
- A literature scan and synthesis based on questions developed by the Issue Paper Advisory Group and conducted by Waterloo’s library staff.

A separate report on Waterloo's research impact was commissioned from Elsevier, using data from Scopus, and is treated as a complement to this issue paper, providing a selective set of indicators that may be treated as a baseline bibliometric data for the new strategic plan.

This methodology was developed not to create a comprehensive understanding of the issue, but rather to highlight and explore the most important issues identified by key University stakeholders.

2.The issues

a. Valuing disciplinary and cross-disciplinary research

The nature of higher education has been constantly evolving since Plato started an open-air academy in an olive grove just outside the city walls of ancient Athens, circa 387 B.C.E., where the intellectually curious could gather and discuss ideas (Brown, 2016). Later in the medieval universities or the *Studium Generale*, as affirmed by Brown, students who wanted to advance to "Masters" or "Doctors" had basically three fields of specialization to choose from: law, medicine, or the "queen of the sciences", theology. But over time, especially during the industrial revolution, new disciplines quickly emerged.

Klein (1990) maintains that the modern connotation of disciplinarity is a product of the 19th century linked with several forces: evolution of the modern natural sciences, the general 'scientification' of knowledge, the industrial revolution, technological advancements, and agrarian agitation. As the modern university took shape, disciplinarity was reinforced in two ways: industries demanded and received specialists, and disciplines recruited students (Klein, 1990). The trend toward specialization was further propelled by more expensive and sophisticated instrumentation within individual fields. Some subspecialties became distinct branches of knowledge.

The modern-day structures of academic institutions began to emerge before and during the Second Word War (Jacobs, 2013). Prior to that, Jacobs affirms, discipline-based departments existed, but were small and did not have the numerous subdivisions characteristic of modern-day academic units.

As disciplines evolved, so did advocacy for cross-disciplinarity. Jacobs (2013) distills the criticisms of discipline-based research that inspired this advocacy. Disciplines, it is charged, inhibit communication, stifle innovation, thwart the search for integrated solutions to social problems, inhibit the economic contributions of universities, and provide a fragmented education for undergraduates. In short, disciplines have become "isolated silos."

Jacobs (2013) challenges the "silo" assumption. He maintains disciplines are dynamic because scholars compete both within disciplines and among disciplines, and disciplines thrive because they create effective research communities. In other words, there are internal and external forces propelling scholarship forward, and there are data (Crane, 2010) indicating that important concepts naturally diffuse across fields and have an impact on disciplinary research.

Jacobs (2013) further posits that discipline formation has been unavoidable in light of the daunting volume of contemporary scholarship. With over 28,000 peer-refereed journals and hundreds of scholarly societies convening regular meetings, specialization into disciplines has been essential for orderly progress. Jacobs makes a case for disciplines combined with the

flexibility to create research centres that function to bridge disciplinary divides and serve as an organizational counterweight to academic departments.

Some would argue that, whether within disciplines or across disciplines, many of the major breakthroughs of the 21st century will likely come from collaborations. The very nature of many modern-day knowledge quests — whether mapping the human brain, using big data to understand health issues in large populations, or developing approaches to restorative justice for marginalized communities — are such that large-scale national and international collaborations will be required. Given the complexity of many of today's challenges, scientists, mathematicians, engineers, social scientists, humanities scholars and artists will have to work together to find a way forward. Climate change is a case in point: researchers divining sources of alternative energy or developing strategies for climate change mitigation will cross paths with those who understand the social impact of climate change (Naylor Report, 2017).

Indeed, the Naylor Report (2017) emphasizes the importance of cross-disciplinary research to Canada and the world:

> *In brief, Canadian society—and the world around us—faces multifaceted challenges that require multidisciplinary approaches to arrive at effective solutions. Canada cannot address tomorrow's challenges based on yesterday's research. We must be positioned to access and adapt the best ideas that scientists and scholars in other countries generate, and to do our fair share in addressing global social and health challenges. (p.20)*

Not all academics agree that this emphasis on cross-disciplinary endeavors will be beneficial. In a *Nature* interview, Graff, author of 'Undisciplining Knowledge: Interdisciplinarity in the Twentieth Century', comments "...too often we frame the disciplines and interdisciplinarity as opposed; the reality is that one depends upon the other". Others, for example Rosenfield (1992), argue that universities should be striving for more integration whereby researchers from across disciplines use shared conceptual frameworks for a specific research endeavor. This cross-disciplinary approach is deemed by Rosenfield to have numerous benefits including the generation of new ideas and new approaches to problem-solving that might not otherwise become evident. She gives as an example a malaria-control project in Brazil involving researchers from different disciplines who brought to the problem the perspectives of the migrant, the mosquito, the malaria parasite, and the social and economic forces that bind these elements together. The result was a much more comprehensive assessment of the problem and new social and epidemiological concepts that gave rise to new disease-control strategies.

i. Barriers to cross-disciplinary research

Question: What are the barriers to interdisciplinary research, and how can they be overcome?

Although academics, policy makers and university administrators often extol the benefits of cross-disciplinary research, the reality is that conducting this type of research is easier said than done. The Naylor Report (2017) acknowledges some of the constraints:

- Researchers may find that their work does not fit readily into competitions and assessment criteria for grant applications or is adjudicated in ways that show puzzling blind spots;

- Multidisciplinary proposals from individuals or small teams of researchers are more likely to be disadvantaged in adjudication when success rates are low and review committees become more conservative in rating grant proposals;
- Challenges also arise due to narrow definitions of merit whereby relevant milestones, such as establishment of collaborative networks or data-sharing agreements, are undervalued;
- Low success rates in getting funded will tend to disproportionately affect the ability of researchers from underrepresented groups and those early in their careers to become established, leading some to leave research altogether; and
- There are continuing difficulties in fairly assessing and adjudicating multidisciplinary research.

The barriers are not just institutional; they can also be conceptual (MacLeod, 2018). A researcher in one discipline may not fully understand the difficulty of the work expected from someone in another discipline. Also, researchers may not want to waste time producing data that might not be used in the final output. Bossio, Loch, Schier, & Mazzolini (2014) note that members of cross-disciplinary groups often begin collaborating in a flush of excitement about a project, but with limited understanding of the complexities involved in navigating traditional disciplinary frameworks. Indeed, Bromham et al. maintain in a *Nature* letter (June 30, 2016) that cross-disciplinary projects require a significant investment of time in building collaborative relationships, developing a shared language and honing a common perspective from disparate viewpoints. Rosenfield (1992) contends that overcoming the barriers to interdisciplinary research will require supportive academic institutions, funding and satisfying career opportunities for those who wish to pursue cross-disciplinary research.

Moreover, not all disciplines are ripe for cross-disciplinary attention. Some areas, like nuclear and particle physics, are unlikely to be cited by researchers in other disciplines. Health, on the other hand, gets more cross-disciplinary citations because it incorporates broad fields such as public health and social aspects of medicine (Van Noorden, 2015).

ii. Fostering collaboration

Question: What are promising practices for enabling collaboration among researchers?

As Waterloo seeks to foster cross-disciplinary collaboration, it is useful to look at what other universities are doing in this realm.

Harris (2010) analyzed institutional documents such as strategic plans, public speeches and reports for 21 research-intensive universities in the United States to identify key drivers of interdisciplinary collaboration. He found that establishing an institutional commitment to collaboration helped to mobilize support for interdisciplinary research and overcome barriers to sustaining collaboration.

Boucher, Smyth & Johnstone (2004) described a two-year Australian research project that involved university staff from two different disciplines and three industry partners tackling the complex issue of nurse retention. They found that there were benefits to the collaboration, such as the ability to study a complex issue and call upon diverse expertise. But there were also challenges, including the fact that university processes prevented equal sharing between academic departments of the financial rewards flowing from the research. The Boucher et al. paper recommends that universities establish processes to encourage and facilitate multidisciplinary research, including the sharing of financial rewards between Faculties.

The Vienna Doctoral Programme on Water Resource Systems, described by Carr, Loucks, & Blöschl (2017), is another relevant case study that provides a framework for management of cross-disciplinary projects. This is an interdisciplinary doctoral program in which students are engaged in cutting-edge international research. Graduates typically get jobs in leading organisations or institutions in the public, private and academic sectors, and the program is popular and deemed to be very successful.

Another approach to fostering collaboration is allocating campus space that brings together researchers from different disciplines. Traditionally, university research space has been allocated in accordance with disciplinary requirements, but with the advent of more interdisciplinary institutes and projects there have been efforts to redesign spaces so that individuals from different disciplines can more easily congregate and develop cross-disciplinary communities. However, case studies show that while alternative spatial configurations can be beneficial, the space itself is not enough.

Friedman & Wordon (2016) examined the spatial configurations of five interdisciplinary centres dedicated to Middle Eastern studies located on US campuses. They concluded that flexible, open space can shift knowledge-exchange and community-building from an occasional to an everyday affair. But success was also dependent on the meaning attached to these spaces, specifically whether they were regarded as welcoming, or more formal and closed. The authors note that dedicated space is a key resource that can be used to encourage interdisciplinary research provided it has clearly designated purpose and meaning. The issue of how to best use space at Waterloo is also highlighted in the Leveraging Resources issue paper.

Baumwol et al. (2011) reported a similar conclusion after examining the impact of a new life sciences centre dedicated to interdisciplinary research at the University of British Columbia (UBC). The new centre was designed to house an expansion of the medical school and, more generally, serve as a state-of-the-art facility for life sciences research. Researchers from three traditional Faculties, Science, Medicine and Dentistry, were asked to organize into thematic groups, with the stipulation that group membership had to be drawn from more than one academic department. The explicit intent was to co-locate faculty in disease or topic-specific groups to increase interdisciplinary research, one of the strategic goals of the university.

Drawing from a survey of faculty locating in the centre, Baumwol et al. concluded that most valued and engaged in interdisciplinary research even though there was initial resistance to the new organizational structure reflecting concern that it would have a negative effect on productivity. Moreover, bibliometric co-authorship analysis and social network analysis indicate that UBC's aim of increasing interdisciplinary collaborations through this initiative is starting to be fulfilled.

Of interest, though, the survey also revealed that most participating faculty perceived that interdisciplinary research is insufficiently valued for career advancement. Moreover, no institutional seed grants were available for supporting increased group integration, nor were the criteria for promotion/tenure/merit altered to reflect the expectations of members of interdisciplinary teams.

These examples illustrate that facilitating interdisciplinary collaboration is not just about bringing researchers from different disciplines together under one roof. It requires active institutional involvement and careful attention to critical issues such as evaluation of interdisciplinary research for career advancement.

In a similar vein, fostering interdisciplinary research collaboration is not simply a matter of introducing new technology. Duysburgh, Naessens, Konings, & Jacobs (2012) examined this issue at the Interdisciplinary Institute for Broadband Technology (IBBT), a research organization in Flanders, Belgium. They found that whilst technology can support collaboration, it does not facilitate it if, for example, it is simply adding unproductive meetings to workload.

Novak, Zhao & Reiser (2014) describe three initiatives undertaken at Florida State University to foster interdisciplinary research, including:

- The development of a faculty research interests/expertise database;
- The establishment of an internal grant program designed to provide research seed funding to faculty, especially those who teamed with faculty from other disciplines, contingent on the recipients seeking additional funding from external sources; and
- The design and implementation of an interdisciplinary research conference intended to promote collaboration among faculty members in several colleges

Roundtables: Collaboration and space issues

Space for research collaboration came up during recent roundtable discussions hosted by the president. Some of the comments from faculty are listed below.

- Internally, diversity is our strength with autonomous Faculties, yet Waterloo does not have a unified approach to doing things.
- It is important to connect people who work on similar issues.
- The Centres and Institutes play a big role in bringing people together:
  - There is a need to get faculty members talking to each other about their research, and develop venues (physical and social) to bring people together.
  - There is no hub for health research. There is a need for a place to bring people together, and a need to have a full picture of interdisciplinary research at Waterloo.
- Faculty members need opportunities to mingle on campus in an informal way.

In order to be leaders, there is a need to bring people together to go after big projects.

3.Research excellence

Question: How should research excellence and impact be assessed?

Defining research excellence is inherently problematic. Many academics feel they are able to recognize research excellence, but in the literature on this subject there is disagreement between among scholars over how to define research excellence, and considerable disagreement about how to measure it.

It is a vague term with many meanings that can be applied in an array of contexts. It can be used to describe a research paper or book, a research project, a researcher, a group of researchers, or even an entire institution. Even within a context, such as excellence of research output within a university department, the measures are not agreed upon and are sometimes seen as insufficient.

Bibliometric measures are commonly used by universities, funders and ranking organizations to assess research outputs. The working group that developed Waterloo's Bibliometrics White Paper (pdf, 1MB) (winter, 2016) concluded, based on peer-reviewed literature and selected grey literature, that bibliometrics offer a useful approach for measuring some aspects of research output and impact. However, the group also noted that there are significant challenges to doing

so accurately, including the expense and time involved in collecting and analyzing the data when resources are limited.

The group cautioned that while bibliometrics can be useful when employed in combination with peer and other expert review, the differences in disciplinary cultures are too strong for most cross-discipline comparisons to be reliable. Indeed, assigning a major role to bibliometric measures for hiring, merit review, and tenure and promotion decision-making is strongly discouraged in the White Paper, and using bibliometric measures alone as a measure for inter-departmental research activity comparisons is deemed to be inappropriate.

In their university ranking website, *Maclean's* assesses the calibre of faculty in part by taking account of major awards including the distinguished Killam Prizes, the Royal Society of Canada awards, and 3M Teaching Fellowships. In addition, the magazine measures the success of faculty in securing research grants from Social Sciences and Humanities Research Council (SSHRC), Natural Sciences and Engineering Research Council (NSERC) and Canadian Institutes of Health Research (CIHR), and, since 2015, has incorporated bibliometric indicators of productivity and impact.

Ferretti, Pereira, Vértesy, & Hardeman (2018) contend that bibliometric indicators are compelling to university administrators and government officials because they put numbers to phenomena that are hard to quantify. One line of criticism (Grupp & Mogee, 2004) stresses that composite scores and rank positions can vary considerably depending on the selection process, and that the use of such scoreboards leaves room for manipulation in the policymaking system. Some academics take issue with the current use of metrics to assess excellence even while they do not deny the theoretical and political relevance of using them. Sørensen, Bloch & Young (2015), for example, argue that the idea of "excellence" has evolved from a fuzzier concept of something that could be revealed through peer reviews to be the type of knowledge that produces breakthroughs. Further, these types of indicators might be an inescapable part of an evidence-based society demanding that policy makers rely on information to identify policy priorities and allocate funds. However, they should not be used alone as a basis for assessing research excellence for the purpose of designing policy (Ferretti, Pereira, Vértesy, & Hardeman, 2018).

Others contend the term "excellence" has been so over-used in higher education as to be almost meaningless, and that the rhetoric of excellence can in fact undermine the very foundations of good research and scholarship (Moore, Neylon, Eve, O'Donnell, & Pattinson, 2017). Indeed, whilst the term "excellence" can be politically useful, it can also impede rather than promote scientific and scholarly activity because it encourages researchers to engage in counterproductive conscious and unconscious gamesmanship. Moreover, it can discourage the intellectual risk-taking required to make the most significant advances in paradigm-shifting research, and the ability to consolidate knowledge in the wake of such advances (Lamont, 2009). In a *Nature* article written in response to a perception of pervasive misapplication of ranking indicators, Hicks et al. (2015) present the Leiden Manifesto of ten principles to guide research evaluation:

1) Quantitative evaluation should support qualitative, expert assessment. Quantitative metrics can challenge bias tendencies in peer review and facilitate deliberation. However, assessors must not be tempted to cede decision-making to the numbers. Indicators must not substitute for informed judgement.

2) Measure performance against the research missions of the institution, group or researcher. Program goals should be stated at the start, and the indicators used to evaluate performance should relate clearly to those goals.
3) Protect excellence in locally relevant research. In many parts of the world, research excellence is equated with English-language publication. Metrics built on high-quality non-English literature would serve to identify and reward excellence in locally relevant research.
4) Keep data collection and analytical processes open, transparent and simple. The construction of databases required for evaluation should follow clearly stated rules, set before the research has been completed.
5) Allow those evaluated to verify data and analysis. To ensure data quality, all researchers included in bibliometric studies should be able to check that their outputs have been correctly identified.
6) Account for variation by field in publication and citation practices. Best practice is to select a suite of possible indicators and allow fields to choose among them.
7) Base assessment of individual researchers on a qualitative judgement of their portfolio. The older you are, the higher your h-index, even in the absence of new papers.
8) Avoid misplaced concreteness and false precision. Science and technology indicators are prone to conceptual ambiguity and uncertainty and require strong assumptions that are not universally accepted. The meaning of citation counts, for example, has long been debated. Thus, best practice uses multiple indicators to provide a more robust and pluralistic picture.
9) Recognize the systemic effects of assessment and indicators. Indicators change the system through the incentives they establish. These effects should be anticipated. A suite of indicators is always preferable to avoid having the measurement become the goal.
10) Scrutinize indicators regularly and update them. Research missions and the goals of assessment shift, and the research system itself co-evolves. Once-useful metrics become inadequate; new ones emerge.

a. Measuring research impact

While academe has well established traditional measures of research impact evaluation, such as scholarly articles in refereed journals, conference papers, scholarly books or monographs, and number of citations, there are reasons for going beyond these traditional measures to evaluate the societal impact of a research endeavour. In particular, some modes of scholarly communication, such as digital or creative arts, cannot easily be accommodated in this traditional framework. This has led to a widening of the scope of research evaluation since the 1990s to include measures of social, cultural, environmental and economic impact (Bornmann & Marx,2013). Indeed, showcasing societal impact has become important in the increasingly competitive funding environment where governments, donors and members of the public want to know the benefits being derived from research investments.

It bears noting, however, that there are few methods of measuring societal impact in a fair, robust and consistent way. Penfield, Baker, Scoble, & Wykes (2014) have proposed using the "Payback Framework," a model for impact assessment that incorporates academic outputs and wider societal benefits. They also discuss the capture of socio-economic impact across disciplines using the Australian Research Quality Framework (RQF), a case study approach, but it is important to note that this approach is cumbersome and time-consuming.

Bornmann & Marx (2013) advocate using an "assessment report", which would summarize new knowledge attributable to research in a field, be written for the non-specialist but reviewed by experts and stakeholders from government and industry, and be made available to the public at large. They contend that this could be part of the secondary literature beyond traditional journals, monographs, handbooks and textbooks.

b. Cross-disciplinary[1] evaluation

Question: What are the barriers to evaluating interdisciplinary work and how can they be eliminated?

Question: What are good practices in evaluating research impact in interdisciplinary contexts?

For cross-disciplinary research, the evaluation process is inherently complicated because it involves different disciplines with different evaluation criteria. A two-pronged approach to evaluating cross-disciplinary research is outlined by Aagaard-Hansen and Svedin (2009). They suggest a review of the disciplinary components of cross-disciplinary research based on respective monodisciplinary criteria, coupled with an evaluation of the cross-disciplinary aspects of the research. The latter would be based on the “problem formulation”, “integration and scope of the disciplines”, “parts and the whole”, “practical managerial aspects” and, if relevant, “the applied aspects” of the research.

Another idea, explored by Mansilla, Feller, & Gardner (2006), is that of creating agile review groups. Members of the groups would be from different disciplines; they would be brought together electronically or via videoconferencing, and they would participate in mediated discussions to address criticisms in real time, ensuring in the process that all members of the group fully understand the nature of the work. Not surprisingly, Mansilla et al. posit there is no single quantifiable formula to measure quality in cross-disciplinary research. However, they do identify some "hot spots" in quality assessment, namely:

- **Focusing on “the right shared problem."** The research and collaborative arrangements need to be genuinely driven by the problem, not the availability of the funding.
- **Establishing social conditions for good work.** The group saw both the bottom-up emergence of a self-assembled research team and the top-down commitments of a leader with a track record of quality work as playing a central role in the potential success of the work.
- **Meeting multiple disciplinary standards.** The work needs to satisfy the quality standards arising from the disciplines involved. If interdisciplinary work is not recognizable as good research by a variety of peers, perhaps it isn’t good research.
- **Reaching effective syntheses**. The capacity to synthesize (especially in transdisciplinary research) is important to advancing knowledge in ways that would have been unlikely through parallel disciplinary means.

[1] For more information on how this paper defined cross-disciplinary and interdisciplinary research, please refer to Appendix B

It will be important moving forward for Waterloo to consider the inherent tensions in evaluating interdisciplinary research, recognizing that our ability to reconcile such tensions will be a significant determinant of the institution's ability to attract and retain talent.

4. Institutional funding

Question: What are promising models for funding single disciplinary research excellence and interdisciplinary research excellence?

In the current funding environment, there are more researchers in more institutions chasing limited research dollars than ever before. This reality is acknowledged in the recent Naylor Report, which notes that Canada's postsecondary research ecosystem has grown considerably since 2000. Although the funding for research in the federal budget has also grown over the past 15 years, its value has been eroded by inflation and an increase in the number of researchers from approximately 33,000 to an estimated 65,000.

This presents a challenge for all research whether single-disciplinary or interdisciplinary, although it would appear to be more difficult to secure funding for interdisciplinary research. The Naylor report contains recommendations for addressing the disproportionate shortage of funding for interdisciplinary research. Specifically, the report contends that more funding is needed for small to mid-scale collaborative projects so that Canadian agencies and researchers can be more effective partners and participants in global science and inquiry.

As the Naylor Report recommendations seem likely to be implemented, it will be important going forward for Waterloo to be nimble in forming cross-Faculty and within-Faculty interdisciplinary teams and developing funding proposals for projects that require working at disciplinary intersections. Also important will be the provision of seed funding to support generation of preliminary data that will enhance the likelihood of securing major external funding for interdisciplinary research. To this end, several University research centres and institutes including the Waterloo Institute for Nanotechnology, Institute for Quantum Computing, Water Institute and Institute for Competitiveness & Prosperity have begun to offer seed funding for cross-Faculty and within-Faculty interdisciplinary research.

Pertinent recommendations in the Naylor Report (p. xxviii) include:

- **Recommendation 6.2:** The Government of Canada should direct the Four Agency Coordinating Board to amend the terms of the Networks of Excellence (NCE) program so as to include the fostering of collaborative multi-centre strength in basic research in all disciplines.
- **Recommendation 6.4:** The Government of Canada should mandate the Four Agency Coordinating Board to develop multi-agency strategies to support international research collaborations and modify existing funding programs so as to strengthen international partnerships.
- **Recommendation 6.5:** The Government of Canada should mandate the Four Agency Coordinating Board to develop strategies to encourage, facilitate, evaluate, and support multidisciplinary research.
- **Recommendation 6.7:** The Government of Canada should mandate the granting councils to arrive at a joint mechanism to ensure that funds and rapid review mechanisms are available for response to fast-breaking issues.

In light of a growing focus on multidisciplinary projects and large collaborations, some universities have deliberately set up seed funding to encourage it. Rons (2011) describes the selection procedures and results of — the 'Horizontal Research Actions' (HOA) program set up at the Vrije Universiteit Brussel in 2002 — to support research collaborations integrating expertise from different disciplines. The program supports networks formed 'bottom up' in integrating expertise from different disciplines. The program's evaluation indicates that it is successful in selecting and supporting the interdisciplinary synergies, responding to a need in the field.

Universities around the world are aspiring to contribute meaningfully to what is being termed in some circles the "next industrial revolution". The joint report of the Committee on Facilitating Interdisciplinary Research, the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine (2004) notes that industry is embracing interdisciplinary research as a means of addressing problems of global scale. It references as an example (p. 48) the large, high-profile consortium announced at Stanford University that is not only interdisciplinary, but includes influential wide-ranging industry sponsors in a 10-year, $225 million project addressing global climate and energy. The project brings together leading scientists from universities, research institutions, and industry to collaborate on fundamental pre-commercial research in hydrogen and renewable energy, CO2 capture and storage, combustion science, and other promising technologies.

It bears noting that Waterloo is disproportionately well poised to engage in collaborative research with industry whether it be discipline-based or cross-Faculty-based. Indeed, as industries increasingly turn to Waterloo to increase their innovation, it will be important to ensure access to expertise broadly across the institution.

5. Recruitment and retention

Question: Should Waterloo invest more heavily in targeted recruitment of senior research stars to enhance its reputation?

Question: Should Waterloo incentivize joint Faculty appointments, and if so, how?

Question: Should Waterloo consider broader implementation of differential teaching loads within academic units, recognizing that running a large internationally competitive research program is increasingly tantamount to a full-time job?

Ultimately, excellence in research, however it is defined, is about people. Whether the research initiatives are driven independently, through involvement in national and international collaborations, or in cross-disciplinary programs within the institution, a university distinguishes itself by the caliber of the people doing the research.

Targeted hiring has traditionally been the practice at many universities. Sa (2008) notes that public university administrators try to focus institutional resources on departments and fields expected to yield the greatest pay-off in terms of enhanced reputation. This leads to prestige-races among research-intensive universities, translating into faculty hiring practices that Burgan (2005) has likened to those of professional sports, where teams vie to recruit "superstars" and the "rookies of the year". Moreover, traditional scholarly evaluation, reward, and promotion systems tend to favor disciplinary and sub-disciplinary rather than cross-disciplinary research expertise and experience.

To overcome the bias against cross-disciplinary research, the Council of Environmental Deans and Directors in the United States has developed guidelines for hiring and mentoring faculty who do not fit standard disciplinary and departmental criteria (Pfirman, et al. 2011). These guidelines are summarized below:

1. The first stage should occur before the scholar is hired, as institutions consider the conditions under which the interdisciplinary scholar will function. These early considerations should include an assessment of whether existing hiring, merit review, and tenure and promotion criteria are appropriate for an interdisciplinary scholar.
2. The second stage is establishment of the interdisciplinary position. It is vital to gain consensus about goals within Faculties and Departments, with special care being given to addressing the service ratio when there are joint appointments.
3. The third stage encompasses the search, hiring and pre-tenure process. This includes defining the process and expectations for all parties, and addressing the logistical needs of the multiple departments or units involved in the hiring.
4. The fourth stage is mentoring of new interdisciplinary faculty hires, bearing in mind that the norms for interdisciplinary scholarship, particularly with respect to publication, are different.
5. The fifth stage is dossier-development and evaluation. As interdisciplinary scholarship is often collaborative, scholars must take extra care to demonstrate their originality, creative thought, identifiable contributions, and capacity for independent scholarship and leadership.
6. The final stage is career development. The Council recommended that resources and rewards, such as merit pay and professional development funds, be made available at the Dean's level or above for faculty engaged in cross-disciplinary research.

Sa (2008) examined the hiring of interdisciplinary faculty at two major U.S. institutions, Pennsylvania State University and the University of Wisconsin-Madison. He concluded that interdisciplinary hiring requires new organizational structures, administrative procedures, and academic orientations. Creating a shared commitment on campus to interdisciplinary hiring appears to be crucial.

It will be important moving forward for Waterloo to be competitive in recruiting and retaining excellent faculty, embracing in the process equity, diversity and inclusivity, which underpin the creation of a dynamic research environment with different perspectives, fresh ideas and new approaches. The Naylor Report emphasizes the need to redress gaps in the professoriate for underrepresented groups, including women, Indigenous researchers, racialized groups, and people with disabilities. A growing awareness of the importance of equity, diversity and inclusivity is forcing universities, including Waterloo, to re-examine recruitment, promotion and retention practices to eliminate unconscious biases. The Naylor Report also posits that the funding agencies can do more to develop recruitment strategies that help build peer review panels more reflective of the diverse composition of the Canadian research community.

6. Waterloo research landscape

Question: Should Waterloo pursue formal institutional research agreements with teaching hospitals?

Question: Should Waterloo pursue a specialized medical school with a strong technical bent aligned with its strengths in physical sciences/engineering?

Understanding the current research landscape at Waterloo is an important starting point for defining the issues to be addressed in the next strategic plan. A number of indicators support the assertion that Waterloo is highly regarded as a research institution. For example:

- Waterloo has consistently placed first as Research University of the Year in the comprehensive category of the Research Infosource ranking over the past 10 years. This is compelling testimony to the high quality of Waterloo research.
- Waterloo currently has 65 Canada Research Chairs (CRC) positions earned on the basis of Tri-Agency funding.
- In funding from NSERC, Waterloo typically ranks fourth among the U15. The Universities of Toronto, British Columbia and Alberta place first, second and third.
- In the *Maclean's* University Rankings, Waterloo ranked first in 2017 among comprehensive universities with respect to SSHRC funding per full-time faculty member, second in 2016 and first in the prior three years (2013-2015). This reflects substantial research strength in the Humanities and Social Sciences.
- In the 2018/19 QS World University Subject Rankings, Waterloo ranked highly in computer science (31st in the world); mathematics (39th in the world); and hospitality and leisure management studies (19th in the world).
- Waterloo is in the top 100 in the 2018/19 QS World University Subject Rankings for civil engineering, chemical engineering, electrical engineering, geography, environmental science, materials science, sports-related subjects and statistics and operational research. It is in the top 150 for mechanical engineering, architecture, psychology, earth and marine sciences, physics and astronomy, and accounting and finance.
- Waterloo is the top school in Canada for computer science and engineering, according to the US News' Global University Subject-area Rankings. Waterloo not only has the largest undergraduate engineering school in Canada, but also produces the largest number of PhD graduates in engineering.
- Waterloo has the highest concentration of computer science researchers, the largest enrolment in mathematics and computer science and the largest number of mathematics and computer science PhD graduates in Canada.
- With respect to collaboration with industry partners, the Leiden rankings for 2017 place Waterloo at the top of the U15.
- In 2017/18, total sponsored research for Waterloo was approximately $225 million, up from $205 million in 2016/17.
- Waterloo currently has approximately forty research centres and institutes that have been approved by Senate. The institution also supports seven University Centres/Institutes conducting cross-Faculty and within-Faculty interdisciplinary research in areas aligned with its strengths. In addition many Waterloo faculty are actively engaged in national and international collaborative networks.

To help us understand the current landscape for cross-disciplinary collaborations at Waterloo, John McLevey, Department of Knowledge Integration, with assistance from Sasha Graham conducted a network analysis of cross-department and cross-Faculty research collaboration (Appendix C). Their report includes visualizations of co-authorships as well as a statistical network model that estimates the extent to which researchers are likely to co-author within or across their Faculties.

Although there are limitations to the comparisons that can be drawn from these analyses, the network data do provide some insights into the nature and extent of collaborative research on campus. For example, it is apparent that collaborations at Waterloo are more likely to occur within than across Faculties, but the probabilities vary by Faculty. Further, the model suggests (not surprisingly) that researchers' existing collaborations influence their future collaborations. One is likely to form new collaborative relationships with existing collaborators. Collaborations emerge organically.

As noted by David Currie in a 2009 article for *University Affairs*, universities with medical schools have an advantage when it comes to rankings and research funding. In part, this is because top-cited articles are strongly dominated by studies with long author lists (e.g., clinical trials).

Waterloo is the only U15 institution without a medical school, yet is a tour de force at the interface between the physical sciences/engineering and medicine. Indeed, virtually all Faculties are, to a degree, engaged in research that has the potential to shape the future of medicine, and not having a medical school could well become a limitation that Waterloo will have to address. Options include creating formal institutional research agreements with teaching hospitals such as Sunnybrook Hospital and the University Hospital Network of the University of Toronto, including the Princess Margaret Cancer Centre, as MIT has done with Harvard's teaching hospitals. Another longer term strategy might be to pursue the establishment of a new, non-traditional medical school at Waterloo, one that has a strong technical focus underpinned by the physical sciences and engineering, yet would arguably enhance Waterloo health-related research broadly across the campus.

7.Summary

The purpose of this issue paper is to highlight current thinking on the future of university research and posit strategic research-enhancement opportunities for Waterloo with a view to catalyzing discussion in the research community that will guide development of the new strategic plan for 2020-2025.

The issues are complex, particularly in light of the ever-increasing competition for limited research funds. They run the gamut from ensuring that the high quality disciplinary research underpinning Waterloo's sterling research reputation flourishes unabated, to seizing new cross-Faculty and within-Faculty interdisciplinary research opportunities. As it maps a future course of action, Waterloo will be aided and abetted by its culture. This institution has been pushing the boundaries right from its inception more than six decades ago. In everything from co-op education to being at the forefront of technological revolution, Waterloo is known as an institution that has dared to be different. A willingness to try new approaches is embedded in Waterloo's DNA.

Moreover, Waterloo faculty are highly regarded by their peers. Indeed, many are internationally renowned and undisputed leaders in their fields. Waterloo faculty have a passion for discovery and a collective spirit of innovation and entrepreneurship that is virtually unmatched. Waterloo is an institution where partnerships and collaborations abound and can grow.

As consultations for the 2020 to 2025 Strategic Plan begin, it will be important to consider not only how to maintain this momentum in research and the reputation it embodies, but also how to surpass it. This will require creativity and resolve. It is hoped that this issue paper will serve as a thought-provoking guide to these consultations.

Appendix A. Definition of terms

The terms 'cross-disciplinary', 'multidisciplinary', 'interdisciplinary', and 'transdisciplinary' are used in overlapping ways to describe research. However, it is important to note that there are distinctions between them, viz.:

- *Multidisciplinary*: researchers from different disciplines working separately on a common project with results published in different venues and with a low level of integration;
- *Interdisciplinary and cross-disciplinary*: researchers working jointly on a common project, while making contributions from their own discipline-specific standpoint; and
- *Transdisciplinary:* researchers using shared conceptual frameworks that are specifically designed and integrated for the purpose of a particular research endeavor.

These distinctions are important, however, in this paper the terms cross-Faculty and cross-disciplinary have been used as umbrella terms for multidisciplinary, interdisciplinary and transdisciplinary research.

Appendix B. Literature review methods

A search of scholarly published literature on research conducted in Universities was conducted using the Education Resources Information Center (ERIC) and Scopus databases. The unpublished literature was searched using Google as well as selected higher education websites such as Universities Canada. The search strategies included search terms such as (interdisciplinary OR multidisciplinary OR cross-disciplinary OR transdisciplinary) AND research AND (evaluat* OR assess* OR measure* OR value OR collaborat* OR fund* OR "best practices"), as well as any associated synonyms. Additional searches were conducted to identify publications on best practices for evaluating research excellence. Due to the volume of literature, search terms were restricted to title-only in ERIC and Scopus, and truncation (the asterisk) was used on some search terms (e.g. evaluat*) to find all possible word endings (e.g. evaluate, evaluated, evaluation). Database search results were restricted to English-only, and a hand-search of *Science* and *Nature* publications was conducted to complement further the database searches.

Limitations

There are inherent limitations to considering how insights from the literature are relevant in the Waterloo context. It is difficult to compare research output across disciplines within an institution, let alone across institutions of varying size and research orientation. It is particularly difficult to assess humanities-based and artistic research across institutions.

Moreover, what works for one institution will not necessarily work for another. While Waterloo can draw some insights and lessons from the experiences of other institutions, it is important to do so through a lens that contextualizes challenges unique to the Waterloo (and Canadian) environment.

Appendix C. Cross-Departmental and Cross-Faculty Research Collaborations on University of Waterloo Campus

John McLevey (Department of Knowledge Integration and Department of Sociology & Legal Studies), with RA support from Alexander Graham (Department of Sociology & Legal Studies)

Overview

This short report is intended to help our committee better understand the extent of collaborative research on campus, and should help inform our conversations about how best to promote research excellence and support collaborations that cross departments and faculties. The network analysis in this report includes (1) visualizations of co-authorships between university departments and across faculties, and (2) a statistical network model that estimates the extent to which researchers are likely to co-author within or across their faculties.

In all of the network visualizations in this report, nodes (circles) represent University of Waterloo departments, and edges (lines) represent co-authorships across departmental lines, or across faculties. The edges are weighted by the number of co-authorships between any pair of nodes (e.g. between computer science and history). In the visualizations, thicker lines indicate higher numbers of co-authored papers between pairs of departments. The edge weights are taken into consideration in the statistical model we developed. The model is discussed below.

To produce these department-level collaboration networks we constructed an author-level co-authorship network from all papers (more than 18,000) indexed by the Web of Science with a University of Waterloo co-author from 2013-2018.[2] Unfortunately, we do not have data on other types of collaborations at the university, so this analysis focuses only on co-authorship.

The data used for the network analysis has some important limitations. First, the Web of Science, like other databases, has relatively weak coverage of journals in the social sciences and humanities. Second, published books are not yet well-indexed. It also has a strong English-language bias. Despite these biases, we think using data from the Web of Science is better than not using any data at all. However, we should keep in mind that **co-authorship in the social sciences, humanities, and creative arts will be underestimated** and therefore less visible.

We linked all authors in the co-authorship network with data provided by the Office of Research and Human Resources on UW employee names and departmental affiliations. We removed all co-authors who are not employed by the University of Waterloo[3] or who do not have an affiliation with a department in one of the six faculties, or with one of the colleges. Finally, we

[2] To those concerned about the use of bibliometric indicators in the context of discussions about how to promote research excellence, please note that the analyses presented here say absolutely *nothing* about productivity or impact. Nor do they say anything about research collaborations other than co-authorship, or about collaborations with faculty from other universities. I had intended to also analyze data on grant collaborations and patent data, but that data was not readily available from the Office of Research. If that data becomes available soon, we can do additional analyses.

[3] Primarily because we do not know their disciplinary affiliations.

aggregated co-authorship to the department level.

Figure 1 shows the collaboration network for individual faculty members across the university. Figures 2-9 show department-level collaboration networks for each of the University of Waterloo faculties plus the colleges. Figures 10 and 11 show Faculty-level collaborations. The specific layouts of the networks vary across figures because the layout algorithm is stochastic.

In addition to these visualizations, we developed an Exponential Random Graph Model (ERGM) of co-authorship across the university.[4] Unlike the network visualizations, this statistical model estimates co-authorship at the level of individual faculty members, each of whom belongs to at least one faculty. Figure 1 is a visualization of that university-wide network, in which each node in the network is an individual faculty member who belongs to both a department and a faculty. Our model estimates the effect that one's faculty affiliation (not departmental affiliation) has on who one forms collaborations with. In network analysis, this is called homophily: "birds of a feather flock together." A positive coefficient for any of the faculties indicates that research in that faculty are more likely to coauthor with one another than would be expected by chance. We produced separate estimates for each of the faculties, plus the colleges.

Each coefficient in Table 1 represents the log-odds of a co-authorship forming controlling for all other terms in the model. A coefficient of 0 indicates that an edge has a 0.5 probability, a positive coefficient indicates a probability higher than 0.5, and a negative coefficient indicates a probability lower than 0.5. The higher the estimate, the more likely that research collaborations are likely to form between researchers *within* the faculty rather than across.

Our analysis suggest that collaborations are more likely to occur *within* faculties than across, but that the probabilities vary by faculty. Our estimates suggest that Applied Health Sciences is the most homophilous faculty on campus (i.e. collaborations are more likely to form within the faculty than across faculties), followed by the colleges, followed by Engineering.[5] The faculties of Environment and Sciences are the least homophilous on campus (i.e. collaborating within the Faculty of Environment / Science is still more likely than collaborating with someone from another faculty, but it matters less than other faculties). In addition to these findings, our model suggests (unsurprisingly) that researchers' existing collaborations have an effect on their future collaborations. More specifically, one is likely to form new collaborative relationships with people who also collaborate with one's existing collaborators. Collaborations emerge organically.

[4] Goodness of fit plots are available upon request.

[5] The differences between Engineering and AHS is Figure 10 are due to the fact that Engineering is much bigger than AHS. Line widths are based on edge weights, which are simply raw counts. Bigger faculties will have more collaborations -- including recurring collaborations -- for obvious reasons.

Cross-Departmental and Cross-Faculty Research Collaborations on University of Waterloo Campus

John McLevey (Department of Knowledge Integration and Department of Sociology & Legal Studies), with RA support from Alexander Graham (Department of Sociology & Legal Studies)

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Table 1: Log-odds estimates of faculty-level homophily in University of Waterloo co-authorship. Not shown in this table: controls for edges and degree 0 - 6.

	Dependent variable
	log-odds of co-authorship
clustering (*gwesp.fixed.0.7*)	2.116^{***}
	(0.096)
cycles / chains (*gwdsp.fixed.0.7*)	-0.020^{***}
	(0.006)
Homophily for Faculty of Applied Health Sciences	2.202^{***}
	(0.408)
Homophily for Faculty of Arts	1.378^{***}
	(0.301)
Homophily for the Colleges	1.609
	(2.230)
Homophily for Faculty of Engineering	1.526^{***}
	(0.214)
Homophily for Faculty of Environment	0.325
	(0.319)
Homophily for Faculty of Mathematics	1.484^{***}
	(0.319)
Homophily for Faculty of Science	0.984^{***}
	(0.222)
Akaike Inf. Crit.	−5,037.205
Bayesian Inf. Crit.	−4,829.400
Note:	*p<0.1; **p<0.05; ***p<0.01

Figure 1: Faculty-level collaboration network used in our Exponential Random Graph Model, reported below. Colors represent faculty affiliations.

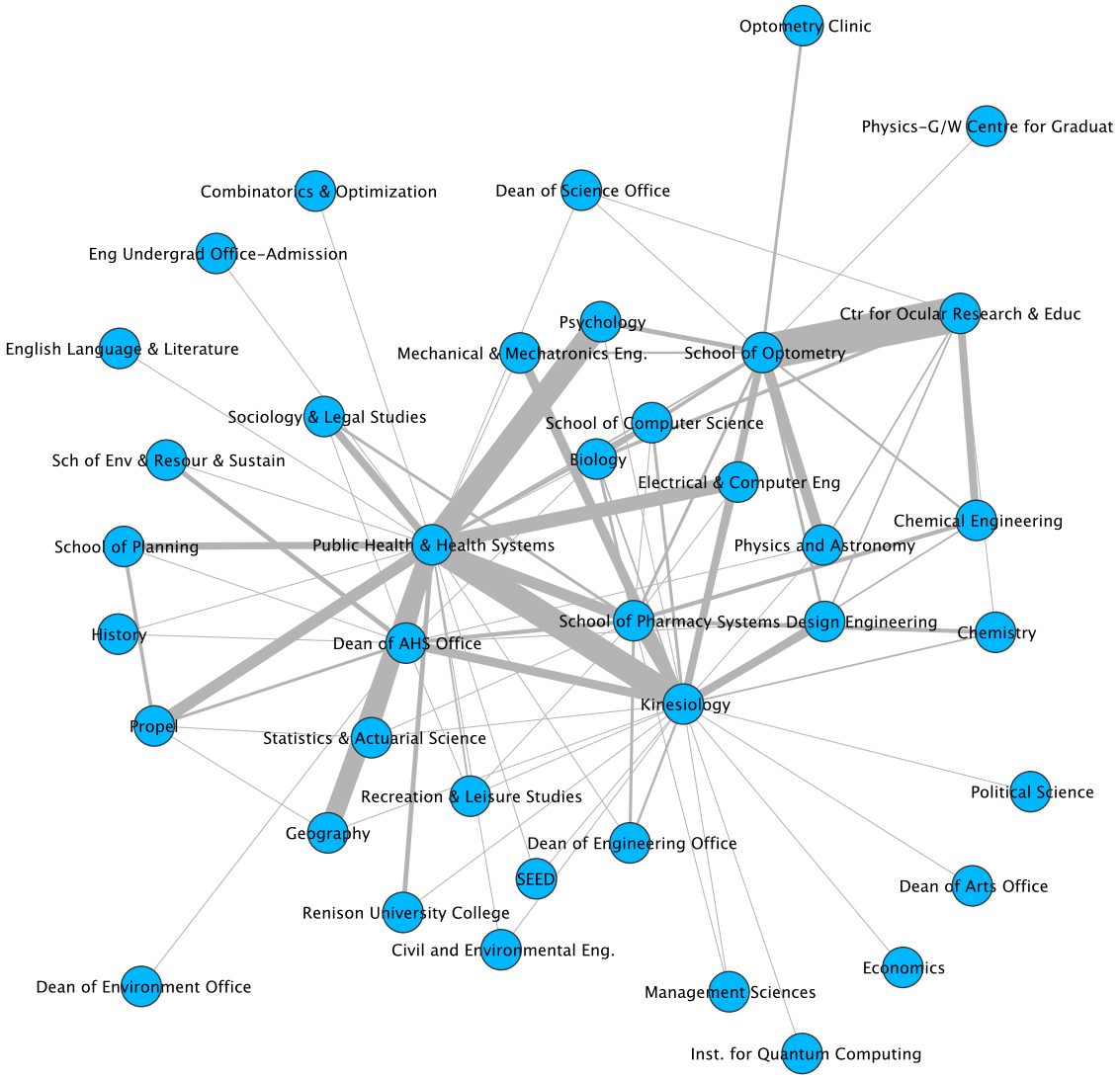

Figure 2: Department-department co-authorship network for the **Faculty of Applied Health Sciences**. Includes collaborations with departments outside of the faculty.

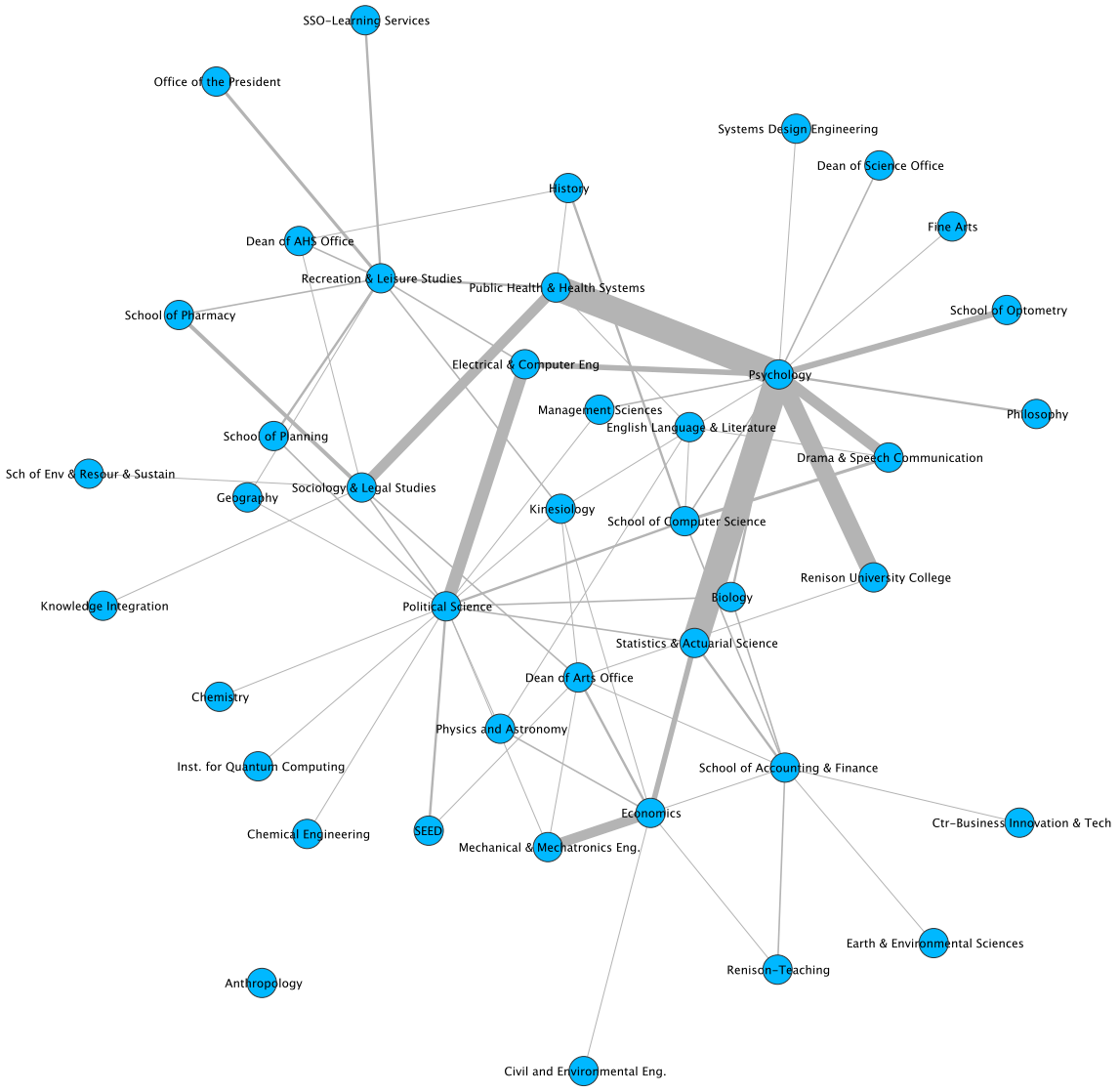

Figure 3: Department-department co-authorship network for the **Faculty of Arts**. Includes collaborations with departments outside of the faculty.

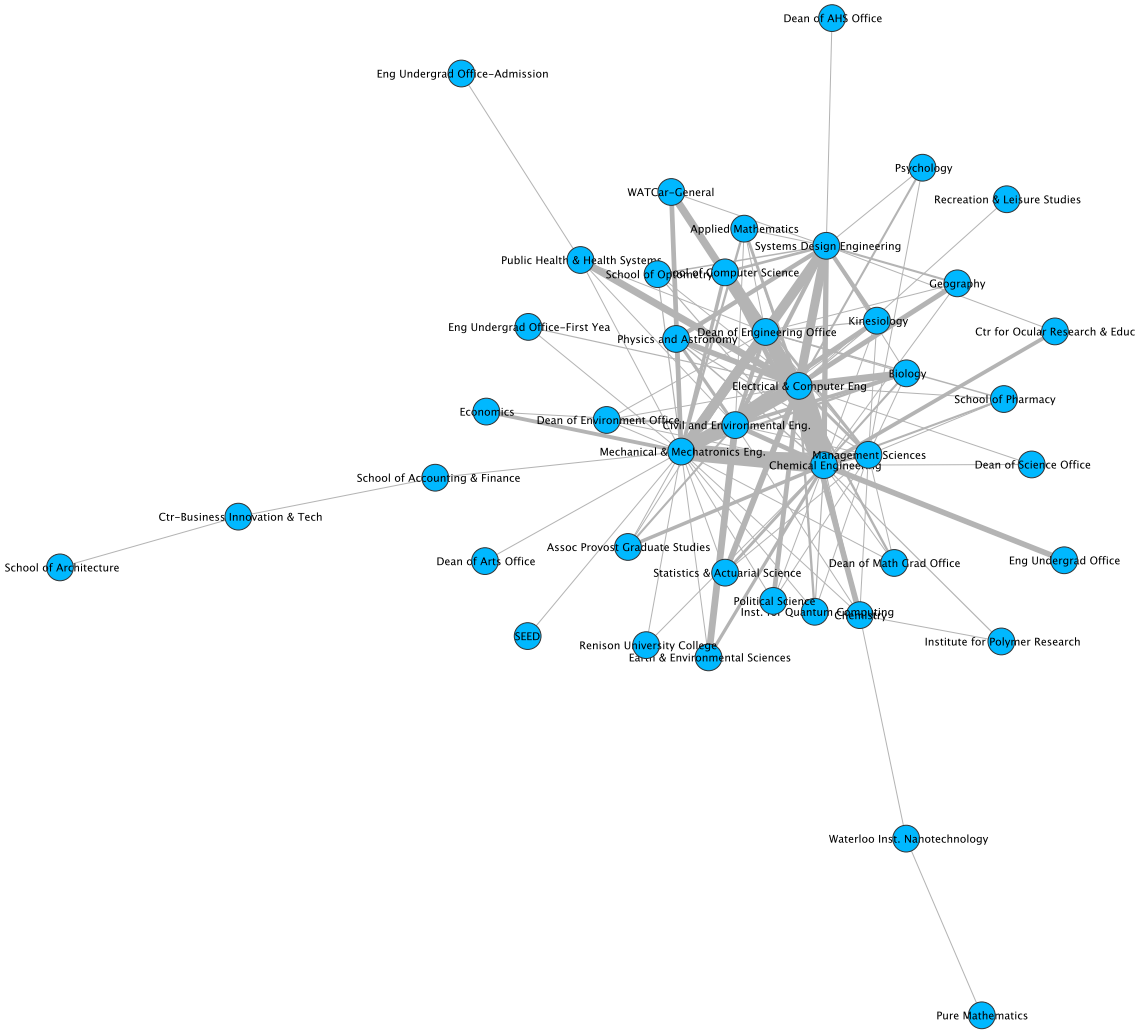

Figure 4: Department-department co-authorship network for the **Faculty of Engineering**. Includes collaborations with departments outside of the faculty.

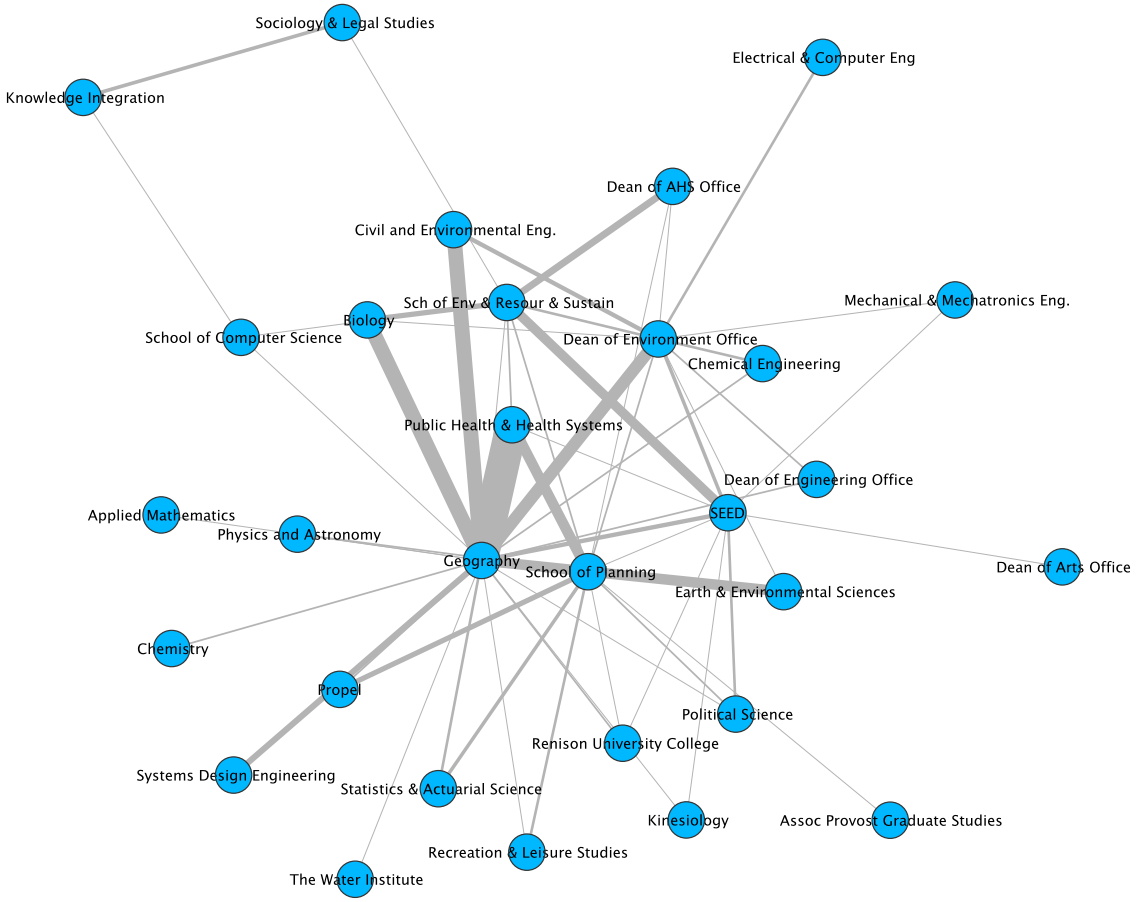

Figure 5: Department-department co-authorship network for the **Faculty of Environment**. Includes collaborations with departments outside of the faculty.

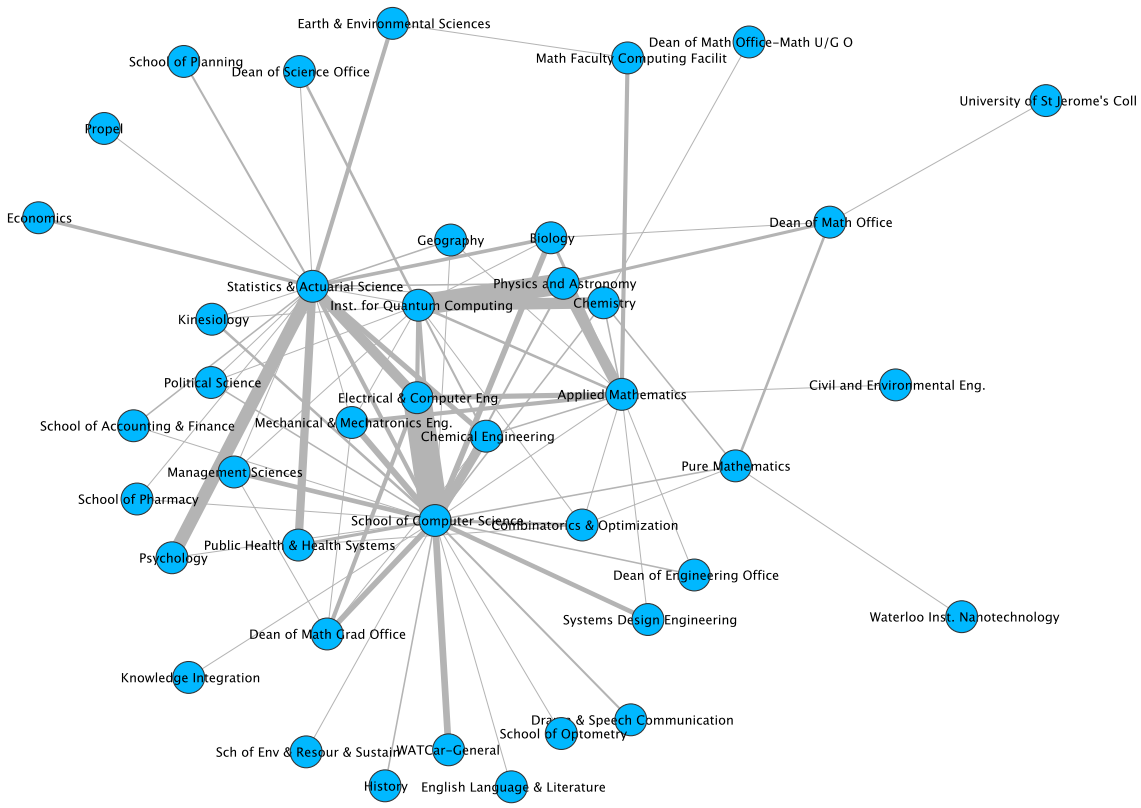

Figure 6: Department-department co-authorship network for the **Faculty of Mathematics**. Includes collaborations with departments outside of the faculty.

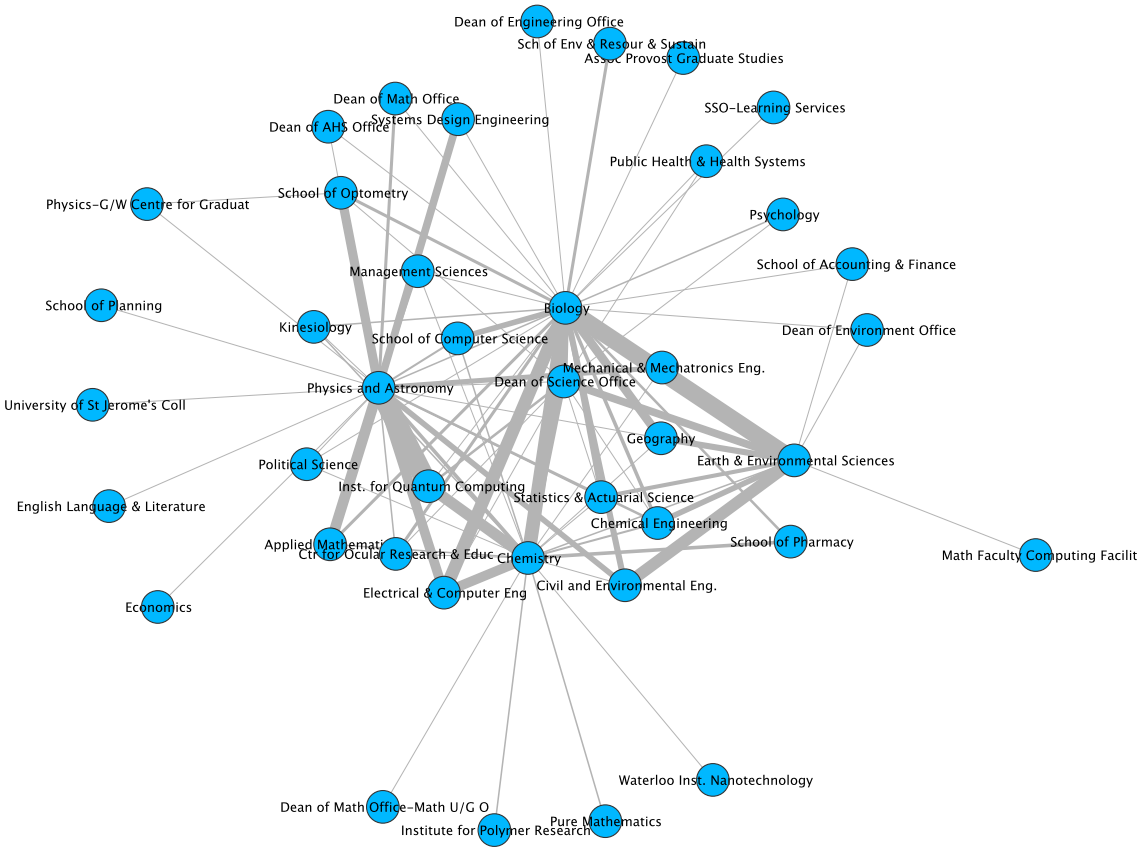

Figure 7: Department-department co-authorship network for the **Faculty of Science**. Includes collaborations with departments outside of the faculty.

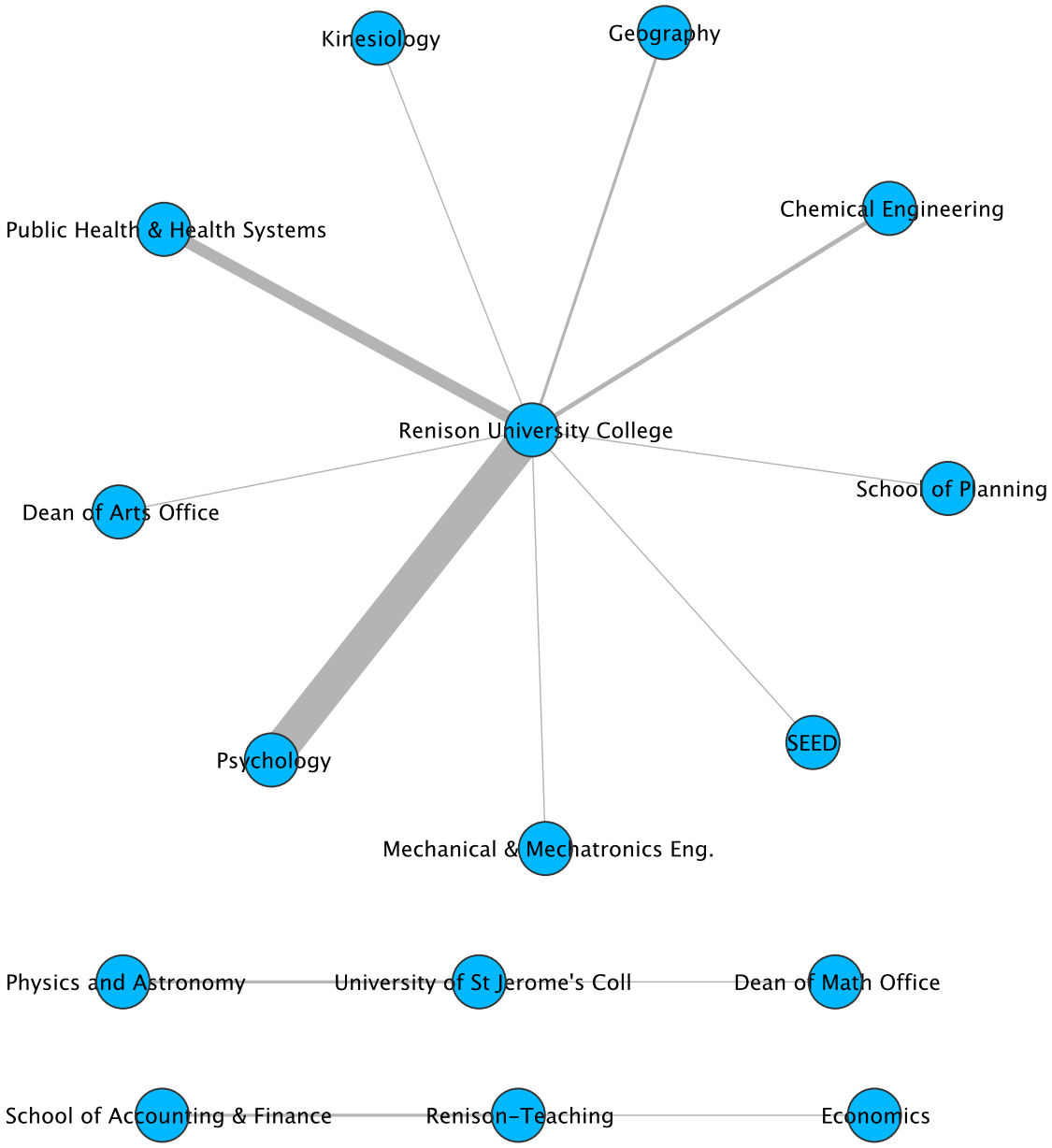

Figure 8: Department-department co-authorship network for **the colleges**. Includes collaborations with departments outside of the faculty.

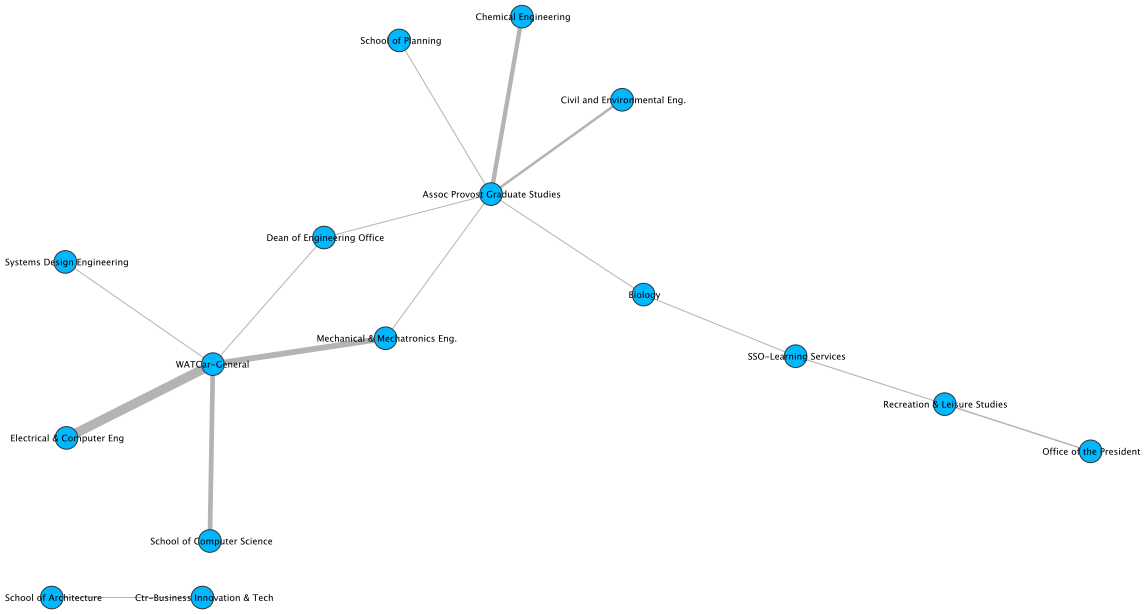

Figure 9: Department-department co-authorship network for **administrative units that are not housed in a specific faculty**. Includes collaborations with departments outside of the faculty.

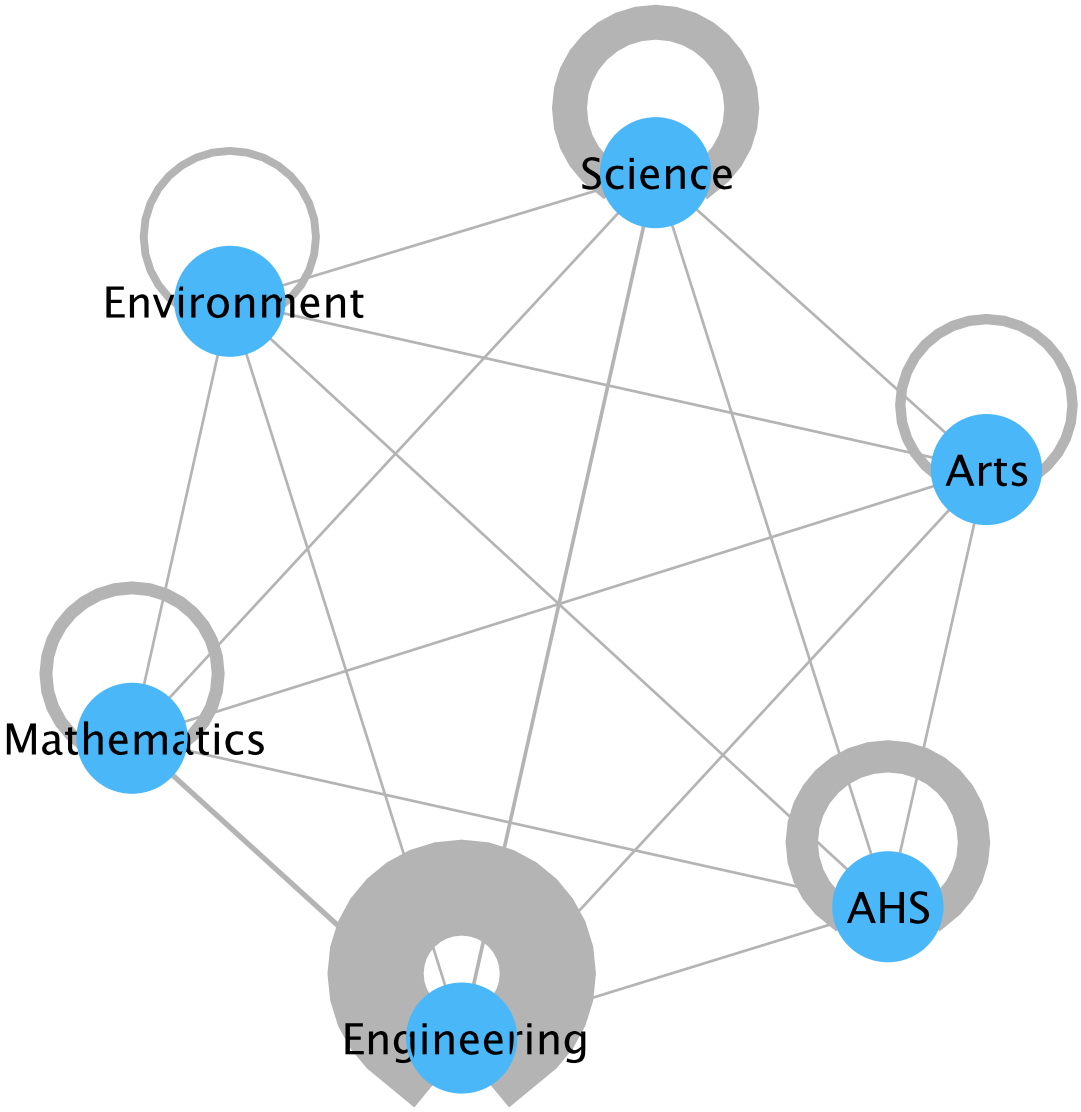

Figure 10: Collaborations within and across the six faculties.

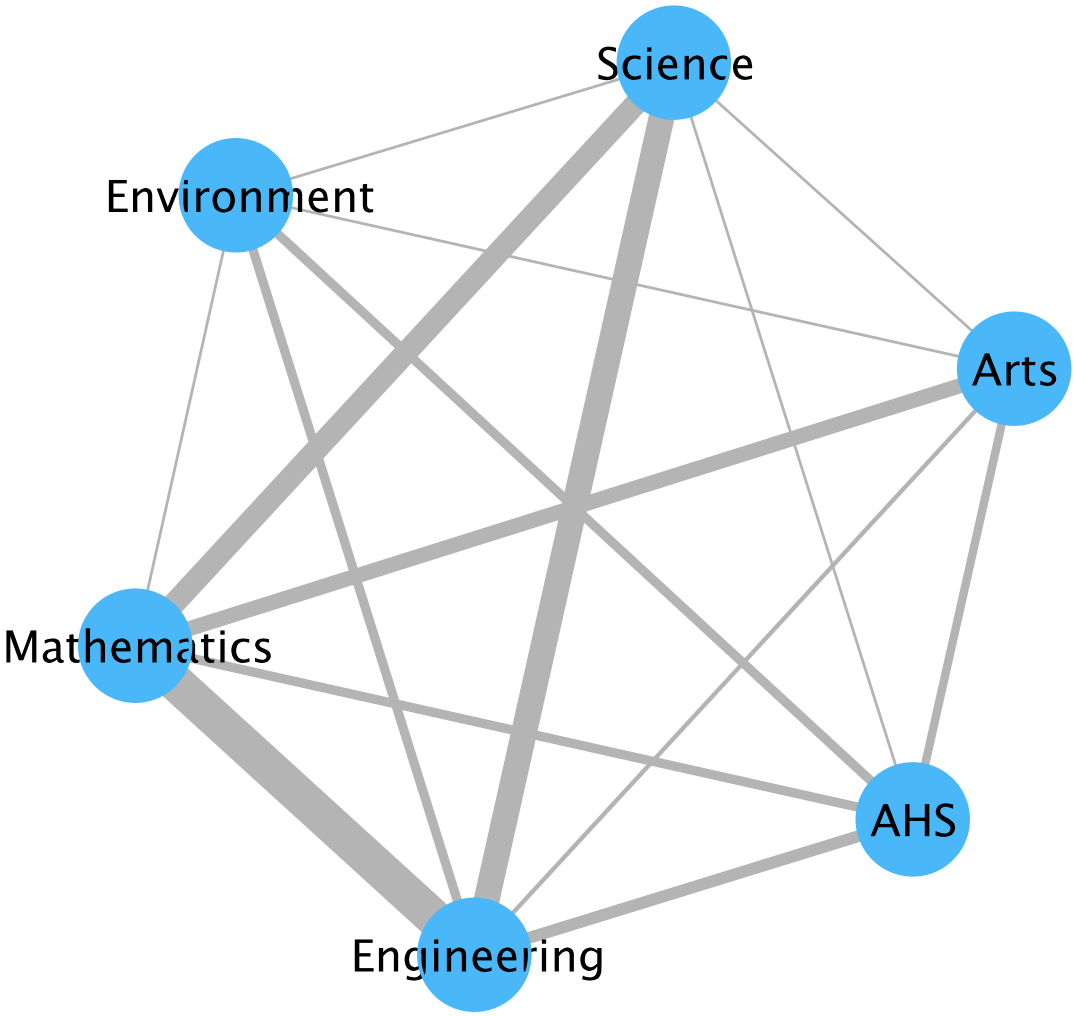

Figure 11: Collaborations across the six faculties.

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