Infrastructure for Interdisciplinarity

EXECUTIVE SUMMARY

<u>Problem</u>

- Much ado has been made of interdisciplinary research (IDR) and its purported and empirically documented benefits.
- Science policy makers likely want to know the wide variety of mechanisms that have been used to facilitate IDR, including: (1) the establishment of research centers; (2) interdisciplinary graduate training; (3) research funding; (4) team collaboration.
- Based on a systematic review of the literature, this policy brief assesses which of these has been most effective.
- The report aims to answer the questions: *What policy might federal agencies pursue to increase interdisciplinarity and hence make more effective use of R&D funding?*

<u>Suggested Policy Changes</u>

- **Recommendation 1:** Continue to support infrastructure initiatives like research & synthesis centers
- **Recommendation 2:** Approach interdisciplinary graduate education via programs like the NSF Research Traineeship program (NRT) with care by:
    - clarifying the type of integration intended
    - making challenges apparent
    - developing standard ways to evaluate training programs
    - training faculty about value of IDR
    - developing clusters of training programs at the same institution
    - beginning with strong disciplinary foundations
- **Recommendation 3: S**upport university efforts to offer seed grants to scholars from different disciplines who hope to jointly develop a research proposal.
- **Recommendation 4:** Fund scholars' efforts generously (in terms of both money and time) so they can make new interdisciplinary connections and overcome challenges associated with IDR. This may entail funding individuals rather than specific projects, and/or broadening the scope of fundable research so that IDR is not confined to a few specific (if timely) issues.
- **Recommendation 5:** Funding agencies can encourage interdisciplinary research by: working with professional associations to encourage cross-disciplinary interaction; being explicit about expectations for interdisciplinary work, and encouraging interdisciplinary team formation at the same university.

<u>Potential Impacts of these Changes</u>

- If recommendations are implemented, the rate of IDR should increase, and thereby possibly fostering innovative and transformative research.

Infrastructure for Interdisciplinarity

A Science Policy Brief
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Theories of innovation suggest that domain-spanning science, including interdisciplinarity, is an important source of innovation. Because pooling non-redundant information (or practices, or technologies) from disparate sources is the foundation from which novel ideas spring (Hargadon 2002, Weitzman 1998), the term 'recombinant innovation' has become almost synonymous with the term 'innovation.' Indeed, few other routes to innovation have been identified. The link between domain-spanning and innovation is so tight that the scholarly literature tends to conflate terms like domain-spanning, integration, interdisciplinarity, and atypicality with innovation (see Lee et al. (2015) for an exception).

Empirical research on recombinant innovation (Fleming 2001, Singh and Fleming 2010, Schilling and Green 2011, Lo and Kennedy in press) and on interdisciplinarity more specifically, confirms that domain-spanning is advantageous. This work suggests that bridging disconnected knowledge spaces results in better ideas that will be rewarded in the marketplace (Lo and Kennedy in press). Support for this comes from numerous studies that have examined the effect that interdisciplinarity has on citations. Atypical and novel combinations of ideas have greater impact (Larivière, Haustein and Börner 2015, Schilling and Green 2011, Uzzi et al. 2013). Fleming's research documents a citation bonus to patents that span patent classes and subclasses (Fleming 2001, Singh and Fleming 2010). Singh and Fleming (2010) found that a research team's experience diversity and network size predict breakthrough patents. Research on the impact of category spanning in science has shown that atypical, category-spanning offerings have higher impact (Larivière and Gingras 2010, Leahey and Moody 2014, Lo and Kennedy in press, Schilling and Green 2011, Shi et al. 2009, Uzzi et al. 2013) as long as the integrated ideas are not too distal (Yegros-Yegros, Rafols and D'Este 2015). Interdisciplinary publications, as a form of atypical, domain-spanning publications, experience these same benefits (Leahey, Beckman and Stanko 2017).

Because of its capacity to spark innovation and generate citations and scholarly influence, **interdisciplinary research (IDR)** – which integrates "perspectives, information, data, techniques, tools, concepts, and/or theories from two or more disciplines" (National Academies of Science, National Academy of Engineering and Institute of Medicine 2005:188) – has been promoted at multiple levels. At the national level, the National Academies of Science published *Facilitating Interdisciplinary Research* (2005) and *Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond* (2014) to foster cross-cutting and potentially innovative research. The White House Office for Science and Technology Policy has investigated how to best foster IDR. The National Science Foundation has accelerated cross-cutting program initiatives like CREATIV[1], interdisciplinary programs like Science of Science and Innovation Policy (SciSIP), graduate training programs like INSPIRE[2], and interdisciplinary research centers. At the university level, administrators are funding cross-department and cross-college research initiatives (Biancani, McFarland and Dahlander 2014, Sá 2008) and supporting the development of interdisciplinary research centers (Berman 2012). Perhaps in response to such policy efforts, individual scholars laud IDR as a 'progressive' 'hot topic' that is 'running rampant;' arguably one 'must be interdisciplinary to be world-class' (Pray 2002). Interdisciplinarity has become "synonymous with all things progressive about research and education" (Rhoten and Parker 2004), and it is clearly a timely and nationally important topic.

For science policy makers, it is useful to know that IDR is beneficial, but is more useful to know the wide variety of mechanisms that have been used to facilitate IDR. Herein, we explore a few in depth, including: (1) the establishment of research centers; (2) interdisciplinary graduate training; (3) research funding; and (4) team collaboration. It is in these realms that federal funding agencies likely have the most power to influence the conduct of IDR. We initially had planned to consider the role of other possible mechanisms, including cluster hiring of faculty and multidisciplinary fellowship programs, but these mechanisms do not fall as cleanly in the jurisdiction of funding agencies (cluster hiring is a university initiative, and fellowships are typically funded by private foundations or university endowments), and the scholarship on these topics is very limited at this time.

What is missing from science policy experts' arsenal is an understanding of which of these mechanisms have been most effective. This policy research report aims to illuminate just this subject by reviewing and comparing the scholarship on research centers, interdisciplinary training, team collaboration, and research funding. I focus on the federal level to answer the question: *What policy might federal agencies pursue to increase interdisciplinarity and hence make more effective use of R&D funding?*

I. Establishment of Research Centers

Since the late 1970s, the United States has witnessed a proliferation of organized research units, and especially problem-oriented **research centers (RCs)** that span sectors and disciplines (Boardman and Bozeman 2007). Funding from federal agencies was critical to this proliferation (Geiger and Sa 2005). In 2016, the National Institutes of Health spent about 9% of its budget, or 2.64 billion dollars, to specifically support research centers (NIH 2016). That same year, the National Science Foundation invested over $210 million dollars to support 68 research centers (NSF 2017:1). If we consider support from other federal agencies, foundations, and universities, it is clear that there have been significant investments in academic research centers.

Most research centers are designed to span boundaries: to either foster connections between two domains of science (academia and industry), and/or to foster connections across disciplines. It is their interdisciplinary function that interests us here. Research centers are intended to facilitate

[1] CREATIV is the "Creative Research Awards for Transformative Interdisciplinary Ventures," a pilot mechanism intended to support bold interdisciplinary projects in all NSF-supported areas of research.
[2] INSPIRE is the "Integrated NSF Support Promoting Interdisciplinary Research and Education."

interdisciplinary research in ways that traditional departments do not—for example, by allowing researchers from multiple departments to work together in an environment that is more responsive to external needs and funding opportunities. Indeed, "[c]enters are a principal means by which NSF fosters interdisciplinary research" (NSF 2017:1). A report in 2012 claimed that most interdisciplinary research at universities classified as having "very high research activity" occurred within research institutes or centers (Nickelhoff and Nyatepe-Coo 2012).

Thus it is no surprise that we find in the scholarship a tendency to presume (rather than examine) the interdisciplinary nature of research centers. For example, Bozeman and Boardman (2013) omit from their sample and analysis all centers that do not have faculty affiliates from multiple departments. Others adopt this same approach (Sabharwal and Hu 2013). While in some ways this acknowledges that some centers may not be ID, it also excludes them from a definition of RCs, or organized research units. Similarly, Jacobs and Frickel (2009) presume that all RCs are ID. This is clear when they propose using the ratio of centers to departments to gauge levels of interdisciplinary research at universities, as this measure presumes that centers are interdisciplinary and departments are mono-disciplinary.

My current SciSIP funded research (award #1461989) suggests that this assumption is not warranted. With Co-I Sondra Barringer and research assistant Misty Ring, I collected data on all RCs (n=9,000) at 157 research universities nationwide. We developed a coding scheme and proceeded to code each RC (its name and associated keyword descriptors) as interdisciplinary or not, with the help of semi-supervised machine learning, a natural language processing technique. Our results show that, in fact, only about two-thirds of research centers are interdisciplinary. It might be useful in subsequent research to compare the kind of research produced at interdisciplinary RCs and other RCs. But this finding has important implications, now, for those of us interested in the question of whether and how RCs foster interdisciplinary research. We cannot expect IDR from RCs that aren't interdisciplinary, that weren't founded with the goal of interdisciplinary research and collaboration in mind.

However, at least one study has found that even centers that are not explicitly interdisciplinary may stimulate IDR. Rogers, Youtie and Kay (2012) study a set of research centers – NanoScale Science and Engineering Centers – funded by the NSF. These centers are not inherently ID, but rather are intended to advance world-class research on nanotechnology, foster technologies for commercial use, and develop a skilled nanotech workforce through education and training. However, the field of nanotechnology sits at the intersection of several established fields of science (p. 374), and Rogers and colleagues' descriptive examination of the distribution of members' publications reveals that "their research contains a very diverse combination of disciplinary content" (p. 345) that even moves beyond the core disciplines of chemistry, materials science, physics, and engineering. Their analysis of forward citations reveals that the diverse research published by center members spawns interest from an even broader scientific community. However, this study makes it hard to attribute such subtle shifts to the centers themselves, because, 1) the centers were founded very soon after the NNI, making pre-center analyses useless, and 2) the size and nature of the program make no part of the field of nanotech untouched by it, making reference groups difficult to find (p. 370). Leahey, Beckman and Stanko (2017) study the population (N=55) of NSF-funded Industry-University Collaborate Research Centers (IUCRCs), which are cross-domain, but not explicitly interdisciplinary. But Leahey and colleagues do measure the extent to which each faculty member actually engages in IDR (and proceed to examine whether and how this influences the quantity and quality of their publications). As part of robustness checks on causal claims and generalizability, they compare scientists' research before and after center affiliation, and compare affiliated scientists with non-affiliated ones. A comparison of mean IDR scores to other studies that have used the same measure (the Rao-Stirling index) with samples of scholars not restricted to RCs reveals that these center-based scientists are slightly more interdisciplinary (Porter and Rafols 2009).

Our literature search identified a number of studies of explicitly interdisciplinary research centers. Smith et al. (2016) also study a specific type of center: Department of Energy funded Energy Frontier Research Centers. They study all 46 centers, but focus on 5 in-depth. While the centers appear to be interdisciplinary, the focus is less on whether they foster IDR and more on whether they promote collaboration and research quality – and they find that they do. Hall et al. (2012) examine six Transdisciplinary Tobacco Research Use Centers (TTURC) funded by NIH and compare them to standard NIH grants (RO1s) that were collaborative and on a similar topic. Results from their longitudinal, quasi-experimental design reveal that interdisciplinary research center grants had higher overall publication rates and productivity was more stable. Moreover, publications produced by the research center grants had greater numbers of coauthors but similar journal impact factors compared with publications produced by the R01 grants. Gaughan and Bozeman (2002) study NSF-funded and university-based multidisciplinary science centers in the fields of biotechnology and micro-electronics. They too find that center affiliation is helpful for obtaining industry funding, and that it improves publication rates. But here, too, the authors do not examine IDR as an outcome. Instead of focusing on a specific center(s), Sabharwal and Hu (2013) focused on one interdisciplinary area – the learning sciences – to examine the effects of research center affiliation. They sampled scholars from this field (based on their voluntary self-classifications in the Community of Science (a database for interdisciplinary scientific research), obtained their CVs, and analyzed data from scholars of varying ranks who worked at research universities. In their comparison of faculty who were and were not affiliated with a university research center, they compared rates of productivity and collaboration. In the field of ecology, there have been several studies of synthesis centers, which support researchers who want to cross traditional divides of method, theory, subfield, and ecological niche (Hampton and Parker 2011).

A subset of these studies goes further by not simply select RCs whose mission is explicitly ID, but also examine whether and how such RCs foster IDR. Two of these studies are single case studies of one center, a third is a comparative case study of centers at a single university, and a fourth studies two synthesis centers. Bishop et al. (2014) studied the National Institute for the Mathematical and Biological Synthesis (NIMBioS) to understand the extent to which affiliation with the center affects the interdisciplinarity of the members' research. Their focus is 46 scholars affiliated with this center, and they collected both bibliometric data and conducted qualitative interview as well. As is common in the literature, the authors rely on the roughly 250 Web of Science subject categories (SCs) to identify members' research areas, but they do not use Porter's measure of Integration (i.e., Rao-Stirling diversity), but rather look at the sheer variety of SCs in each member's research program. Bishop et al. (2014) employ an interrupted time series quasi-experimental design that focuses on comparisons pre- and post- center affiliation, so internal validity is stronger than most studies of this kind, even if external validity is limited. Their quantitative analyses reveal that center affiliation has no significant effect on interdisciplinary research (i.e., the variety of fields one publishes in), but qualitative data show some shift in focus over time, toward more mathematical fields. Had the authors used a more nuanced measure of interdisciplinarity that accounts for the nature of the fields and the distance among them, perhaps they would have found a significant change. The five individuals whose productivity was most enhanced by center affiliation did indicate that the experience led them to "collaborations with researchers from other disciplinary fields that would not have occurred" otherwise (p. 334). Yang and Heo (2014) assess whether the first government funded university research center program in Korea has been successful in fostering interdisciplinary collaborations. Their network analysis of a sample of research publications (n=102) resulting from one Center funded by the program reveals that the program fosters the dissemination of knowledge across a broad range of fields. Biancani, McFarland and Dahlander (2014) examine three research centers at Stanford University, all of which have an interdisciplinary focus like Biotechnology, Environmental Science, or International Relations. Using longitudinal data on faculty members' activities before and after joining the center, they find that center affiliation promotes the establishment of new ties between faculty members – in terms of both coauthoring publications and grant proposals. While much research has focused on formal organizations and even informal organizations, their work suggests that semiformal organizational forms are also critical, and can be quite effective in stimulating connections among scholars form different fields. And lastly, a working paper by Ed Hackett, John Parker, and colleagues (including myself) finds that scholarly work that originates within synthesis centers is more diverse in terms of the number and variety of topics they touch upon.

- **Recommendation 1:** Continue to support infrastructure initiatives like research & synthesis centers

2. Interdisciplinary Graduate Training

Whereas the scholarship on centers focused almost exclusively on faculty affiliates, the scholarship on graduate training programs helps us understand how to best foster interdisciplinarity among the next generation of scientists. The focus in the literature, and here, is on programs funded by NSF and other federal agencies, such as IGERT, INSPIRE, and NRT, though of course universities can also forge ahead with interdisciplinary graduate programs without federal funding. Mitrany and Stokols (2005) note that evaluations of graduate training programs tend to fall into one of two camps: 1) those that assess training in situ by examining curricula, exchanges, interactions, and mentoring relationships, and 2) those that assess the quality and scope of the products of such training.

Assessing training in situ

Studies that fall in the first camp tend to be in-depth, small, qualitative case studies that focus one or a few graduate training programs. Holley (2009) conducted 45 interviews with faculty and students associated with a neuroscience program, and found that beyond the formal curriculum, diverse disciplinary electives, the broader cultural and social influences at the university, and a deliberate process to foster integration were critical. Ryan et al. (2012) studied only 12 graduate students in the Canadian Centre for Youth and Society, but identified factors that likely contribute to the development of graduate student research capacity, including: interdisciplinary hands-on training; mentoring;

knowledge exchange and networking; funding; and supportive working environments. In their study of centers for Tropical Agricultural Research and Higher Education, Morse et al. (2007) found that *it is important for teams and programs to identify the type(s) of integration they will pursue, and to be cognizant of the challenges they entail.* They too found that not only planning but also continual reflection throughout the project was necessarily to foster IDR successfully.

Several studies by Maura Borrego and colleagues (Boden, Borrego and Newswander 2011, Newswander and Borrego 2009) focus on clusters of NSF IGERT programs at two universities. Based on their analyses of interviews, focus groups, and site visits to these two universities, they found that student experiences were more positive when engagement, participation, and connections were emphasized and when learning was interactive. Although student satisfaction is an important aspect of program success, it is less relevant to our goal of assessing whether interdisciplinary graduate training actually fosters interdisciplinary research. Borrego and colleagues argue that special attention should be paid to overcoming organizational barriers to interdisciplinarity related to policies, space, engagement with future employers, and open discussion of the politics of interdisciplinarity. If and when these hurdles are reduced, engagement with interdisciplinary research should increase.

Much can be learned from these case studies, especially when they are linked to broader data. For example, Borrego and colleagues (2014) analyzed 114 NSF IGERT proposals from a large swath of universities and creatively link these data with interviews and observations they conducted at two universities that received multiple IGERTS. Their goal was to assess whether and how proposals discuss possible whether and how the IGERT initiatives and mission will be institutionalized after NSF funding ends. The key insight emanating from this study is that regulation (by NSF or university administrators) is by itself insufficient; cultural and normative changes are also required for institutionalization to succeed. Certainly, NSF and other funding agencies can expand definitions and requirements regarding institutionalization and develop widely accepted means for evaluating the impact of institutionalization and change efforts. But cultural change is critical, especially for older cohorts of faculty who might need some re-education about the value of IDR before they judge theses, dissertation, job applicants, and P&T dossiers. While cultural change is challenging, it might be easier to effect at institutions in which a critical mass emerges; the institutions that Borrego and colleagues (2014) studied had received multiple IGERT grants, and this may well have pushed commitment to IDR to a broader and deeper level than would be the case at universities with a stand-alone program. In this way, funding agencies' decisions about whether and where to concentrate (or diversify) their efforts may be critical.

Assess the products of training

Studies that fall in the second camp tend to be quantitative and rely on secondary data and/or bibliometric data. Probably the best example of this is the small quantitative study by Carr et al. (2017). They conducted a case study of one interdisciplinary graduate program in water conservation policy, whose goal was to develop an interdisciplinary approach and produce cutting edge research. Using the disciplinary home of coauthors to identify interdisciplinary papers, they find that "this programme is leading to a substantial portion of research that is cross-disciplinary in nature" (p.9) and that research emanating from interdisciplinary teams is published in higher impact journals and receives more citations. Another excellent example is Mitrany and Stokols (2005), who examined 150 dissertations produced from one interdisciplinary graduate training program. They developed objective measurement criteria that they hope "can be used to assess the transdisciplinary qualities of diverse training programs and research projects" (p.441): interdisciplinarity of the topic, committee, and methods; the geographic and temporal scope of the research, analytic level(s) used, and whether attempts were made to translate research results into recommendations. They found that smaller and more multidisciplinary departments were most effective in helping students produce dissertations with transdisciplinary qualities. It would be interesting to see whether and how this translates into post-dissertation interdisciplinary scholarship. Mitrany and Stokols (2005) argue that "a potentially important strategy for promoting the transdisciplinary development of doctoral students is to foster change in the attitudes of faculty members teaching in graduate programs" (p. 447), because these individuals supervise and mentor the next generation.

We located two additional quantitative studies that rely on large scale survey data: the SED/SDR data collected by NSF on doctorate recipients in the U.S. (Kniffin and Hanks 2017, Millar 2013). Here the focus is less on the programmatic elements of graduate training, and more on how individuals PhD students who choose to write ID dissertation fare in the labor market. Kniffin and Hanks (2017) find that they are more likely to accept a post-doctoral position, and partly because of this, they earn less income (they do not assess whether this is the case because ID dissertations are more likely in fields where post-docs are more common). To the extent that NSF and science policy is concerned about the rise of post-docs and especially post-docs that don't serve as a stepping stone to tenure-track employment (and the rise of contingent faculty more generally), these findings are relevant beyond individual career strategizing, and would be more so if they supplemented their analysis with the panel of SDR so careers of young scholars could be followed over time. Digging more deeply and theoretically into Kniffin and Hanks' (2017) finding that certain types of PhD students (international students, upper middle class, and women) are more likely to pursue ID may also help NSF and higher education administrators expand and tailor programs to a broader swath of students. Millar (2013) also used the large NSF surveys of PhD recipients to show that graduate students who pursue ID dissertations are more likely to obtain a position in academia rather than industry or government, and given this, they are also likely to report higher productivity in terms of research articles. For us to understand whether/how ID graduate work actually spawns ID work, we need to link the self-reports available via SED to their publications, and barring that, we need to use ID dissertation as the outcome of interest and obtain more information about the nature of graduate training.

One unique study bridges the two camps by examining both exchanges and interactions that take place, but they do this after the interdisciplinary training took place, and outside of its typical space. Hackett and Rhoten (2009) conducted a fascinating charrette experiment that compared groups of IGERT-trained and traditional (disciplinary) graduate students, found that IGERT training, at least in the early years, improved the quality and process of collaborative research. However, among groups comprised of older (3rd and 4th year) graduate students, the two IGERT-trained groups' work was evaluated as less original and less successfully interdisciplinary. Based on observations of group dynamics, Hackett and Rhoten found that IGERT students focused on form over content: they got bogged down in *enacting* rather than *being* an interdisciplinary, collaborative team – they were aware of the rules but could not fulfill the associated roles. This, they suggest, might be attributable to a reversion to conventional, disciplinary roots in later years, as advanced graduate students encounter "the more treacherous waters and institutional realities of a nascent professional career (culminating in the prospect of a discipline-dominated job market)" (p.424). Based on these findings, Hackett and Rhoten (p.427) encourage training programs to start with a strong disciplinary foundation before moving into interdisciplinary immersion. This perspective aligns well with Jacobs' (2014) argument about the critical role of disciplines, and Foster and colleagues (2015), who find that some of the best interdisciplinary innovations often come from the tension with disciplinary traditions.

- ❖ **Recommendation 2:** Approach interdisciplinary graduate education via programs like the NSF Research Traineeship program (NRT) with care by:
  - clarifying the type of integration intended
  - making challenges apparent
  - developing standard ways to evaluate training programs
  - training faculty about value of IDR
  - developing clusters of training programs at the same institution
  - beginning with strong disciplinary foundations

3. Funding

Funding is required to established research centers and interdisciplinary graduate training programs (which in turn appear to foster IDR), but research grants may also have a direct positive effect on IDR. Although "the literature on the strategic management of interdisciplinarity at the national programme level is …sparse" (Lyall et al. 2013:63), we were able to locate a number of studies that examine whether and how funding can promote IDR. The scholarship, and thus our review of it, focuses on external funding, mostly from federal agencies, and finds that "external funding is one effective means to incentivize research spanning the natural and social sciences" (Garner et al. 2013:142). Although "universities are not necessarily organized to foster IDR" (Garner et al. 2013:142), we searched specifically for university-level policies and practices that may be stimulating the integration of experts and subject matter from diverse disciplines.

Although internal grants are a direct and quick way to stimulate IDR on campus quickly (Sá 2008), our systematic literature search turned up few studies of how internal (university-sourced) funding influences research, especially IDR. One exception is an article by Paller and Cerra (2006), which reports one university's experience with an internal grant program designed to foster interdisciplinary collaboration. The internal awards they study are larger than most internal grants $200,000 for 1-3 year projects, so results might not apply more broadly. To be eligible for the funding, the project needed to include investigators from more than one college or school at the university. While the research teams were multidisciplinary, the authors do not examine whether and how the internally funded projects stimulated IDR. Rather, their outcomes of interest included self-reported information on subsequent grants, publications, and the development of new collaborations.

We located one study that examined how external grant money was used to facilitate and fund an internal grant program specifically designed to foster IDR. Denne et al. (2013) report on programs at two research universities in the U.S. that were funded by the NIH's Clinical and Translational Science

Awards program. These two programs were designed to encourage IDR and to foster ID team development. They used the NIH award to create what they call project development teams at each university. These teams - which comprise experienced investigators, statisticians, and staff with expertise in IP, commercialization, and research regulation – provide consultation and project management assistance to researchers (especially those in an early career stage) seeking assistance with grantsmanship. As the authors state, both programs found that "pilot funds can be used not only to engage investigators, but also to influence their research interests, approaches, and collaboration choices" (p. 63). In addition to spawning external grant dollars, patents, and start-ups, the programs facilitated 32 new collaborations between social and clinical scientists, and engaged faculty from 88 different departments across the institutions – giving some good indication that the mission of promoting IDR was achieved.

- **Recommendation 3:** If possible, support university efforts to offer seed grants to scholars from different disciplines who hope to jointly develop a research proposal.

Of the larger number of studies that examine the impact of external funding on IDR, we were particularly impressed with work by Jon Garner and Alan Porter and colleagues (Garner et al. 2013, Garner et al. 2012, Porter, Garner and Crowl 2012). Their 2012 companion papers assessed whether and how NSF's Research Coordination Network (RCN) program enhanced ID publication. Although randomized experiments are almost impossible to execute in this context, they use the best alternative: a non-equivalent control group design that compares outcomes across treatment (RCN funding) and control groups (no RCN funding), and across time periods (pre- and post-RCN funding). RCN provides funding support for networking and collaboration among scientists working on similar themes (rather than research funding), and seeks to "catalyze development of research areas that grow at the shared margins of more conventional fields of study" (Garner et al. 2012). Relying on Porter's nuanced Integration score to measure interdisciplinarity (which examined fields represented in a paper's bibliography, and incorporates number of fields, the evenness of their distribution, and the dissimilarity between them), they find from a comparison of before- and after-RCN publications that RCN boosts interdisciplinarity by about 10%. Of the 13 RCN projects they examine, 11 show an increase in the Integration score after RCN funding. This modest but significant increase over time was not apparent for the comparison groups that did not receive RCN funding. Their 2013 paper examined the research fostered by the unique NSF program Human and Social Dynamics (HSD), which requires project teams to represent at least two disciplines, and include at least one social or behavioral scientist. Garner and colleagues (2013:136) analyze publications derived from HSD funding in 2—4 in order to "evaluate the effectiveness of this Federal funding initiative in promoting IDR." Compared to two carefully constructed reference groups, HSD funded projects demonstrate more disciplinary diversity in terms of both backward citations (what they reference) and forward citations (the papers that cite them). They conclude that "IDR that successfully integrates natural and social sciences can be promoted through targeted funding investments and specific requirements in grant solicitations" (p.143).

Others used a similar research design. To evaluate the NSF's Research and Evaluation on Education in Science and Engineering (REESE) program, Milesi and colleagues (2014) also employ both a comparison group as well as a focused study of REESE PIs to compare their productivity before and after the program. They study 323 investigators from 402 different projects that were funded between 2006 and 2012. They coded data from CVs posted online and solicited via email from the PIs. Their comparisons of REESE PIs with other PhD holders (obtained from the Survey of Doctorate Recipients 2008) reveal that the REESE PIs are particularly productive. Their interrupted time series analyses also reveal that the REESE program also helped these PIs increase both the quantity and quality of their research.

A few recent studies forgo a comparison group, and focus instead on describing the research that emanates from funded projects. For example, Taskin and Aydinoglu (2015) use bibliometric data and network and mapping techniques to understand the kind of research emanating from the NASA Astrobiology Institute (NAI). They focus on the 1210 publications that resulted from NAI funding and were listed in annual reports from 2008-2012. They examine a number of outcomes, but the most relevant here is their focus on the disciplinary categories of the published work. To examine this, they rely (as many do) on the Web of Science subject categories that describe journals. They find that although the most common category is, as we might expect, Astronomy & Astrophysics, over one-third (34.5%) of papers were inter (or at least multi-) disciplinary, as indicated by the journal of publication being categorized in two or more subject categories. The NAI has promoted IDR, and has been encouraged to track whether and how its resulting articles are ID. Paper-level measures of IDR were not used here, but might reveal a higher level of IDR engagement. Huang et al. (2016) also focus on funded research, and examine research proposals and their resulting publications as well. They focus on the field of Big Data and compare federally funded research in the U.S. (by NSF) and in China (by the National Natural Science Foundation). Their comparison of over 1000 publications reveals that big data research in both countries pertains largely to two fields – Electrical Engineering as well as Computer Science & Information Systems – but cover many of fields as well, suggesting that "Big Data research is not bottled up in a silo" (p.13). They find that both agencies address the rise of Big Data in an interdisciplinary way, but the NSF relies more on co-funding from multiple programs. In the U.S. context, they examine the program element and program reference codes that NSF assigns to grants (which do not, based on my own investigation, identify unique programs) and find that almost two-thirds of proposals fall into only one program. They go on to use these program codes to develop a continuous measure of interdisciplinarity and show that it increased between 2011 and 2015.

Although we must be cognizant of publication bias, the published studies we located together show that both internal and external funding can bolster IDR. All of the studies we reviewed above were based (or partly based) in the U.S. context. But there are a lot of similarities between the U.S context and the U.K. context studied by Lyall et al. (2013). They studied five large, nationally funded, and interdisciplinary research projects in Britain, supplemented with 14 interviews. Their comparative case analysis allowed them to derive some suggestions for funding agencies seeking to promote integration across disciplines in an effective manner. For example, they find that IDR takes place over time and proceeds in multiple stages; thus, funders "will need to recognize the validity of any additional time and expense spent on tailored 'catalytic' activities at various stages throughout the programme's lifetime" (p. 66). They also find that active management is critical, but few academics are trained in management skills; thus, funders need to actively support such training if they hope to promote effective IDR. Funders must also recognize the additional time required to effective integrate diverse disciplines and allow for such flexibility in timelines and budgets (p. 69). This is consistent with McBee and Leahey (2016), who document the diverse challenges that interdisciplinary scholars face, and with Leahey, Beckman and Stanko (2017), who find that IDR depresses scholars' productivity because there are large cognitive and communication obstacles that scholars confront when they plan, coordinate, and conduct their research. Lyall and colleagues (2013) also found that programmes that dispersed funds in successive funding rounds had more opportunities to review performance and adjust foci and funding priorities when need be.

Our own ongoing research investigates whether interdisciplinary programs, like NSF's Cross-Cutting programs, may help foster research that is more interdisciplinary. NSF's Cross-cutting (XCUT) programs give scientists an opportunity to secure funding for their discipline-spanning research, and may also prompt them to design and craft and write their research in a way that more effectively engages the interest of multiple disciplinary audiences. In my current SciSIP funded research (award #1461989), Sondra Barringer and I find that cross-cutting (XCUT) NSF programs have a positive effect on the establishment of research centers at universities nationwide, which themselves foster IDR. Jina Lee, research assistant on this report, has conducted LDA topic modeling on the abstracts of Cross-cutting (XCUT) NSF grants awarded 2004-14, revealing that some XCUT grants focus on timely topics that are widely recognized as interdisciplinary (e.g., water, sustainability, energy), but many focus on traditional, disciplinary fields. Perhaps this suggests that XCUT grants are best used to stimulate research on practical, policy-relevant problems, but may not necessarily foster new connections across disciplines. Once our research is completed, we will be able to make recommendations about where to target federal research funding.

- **Recommendation 4:** Fund scholars' efforts generously (in terms of both money and time) so they can make new interdisciplinary connections and overcome challenges associated with IDR. This may entail funding individuals rather than specific projects, and/or broadening the scope of fundable research so that IDR is not confined to a few specific (if timely) issues.

4. Interdisciplinary Collaboration

My previous work on research collaboration suggests that collaboration and interdisciplinarity are typically confounded, but this linkage is not warranted. As I document elsewhere (Leahey 2016), collaboration can occur across disciplines, but it may also occur across sub-disciplines (Leahey and Moody 2014), nations (Xie and Killewald 2012), domains of science (Smith-Doerr and Vardi 2015), and universities (Cummings and Kiesler 2005, 2007, Jones, Wuchty and Uzzi 2008). Leahey and Reikowsky (2008) identify multiple types of collaboration, not all of which represent a joining of experts from different topic areas. And lastly, Leahey and McBee's (2016) study of scholars in the humanities makes clear that interdisciplinarity doesn't have to be collaborative at all.

Some recent papers notably focus on interdisciplinary collaboration, and are careful to distinguish it from disciplinary collaboration. Two of these studies are interview based. Boix-Mansilla, Lamont and Sato (2016) identify the varied characteristics of successful interdisciplinary collaborations, including cognitive, interactional, and even emotional aspects. Borrego and Newswander (2008) focus on the joining of engineers and social scientists – specifically how they locate and select collaborators, how they join their strengths, and how they divvy up tasks. Woolley et al. (2015) take a different approach. Based on a survey of almost 700 Australian-based social scientists, they find that certain factors – like international citizenship and an orientation toward applied research – are critical to fostering interdisciplinary (but not disciplinary) collaboration.

A number of these studies examine the conditions that promote ID collaboration, and what policies and practices might be invoked to foster it. Based on their interviews, Borrego and Newswander (2008) provide recommendations for multiple stakeholders. They suggest that funding agencies and professional societies continue to fund interdisciplinary research, facilitate cross-disciplinary interactions, and be explicit about expectations. They suggest that university administrators reduce barriers between academic units (to allow for shared grants and team teaching) and host meetings on important interdisciplinary topics. And lastly, Borrego and Newswander (2008) recommend that faculty be aware and upfront about issues pertinent to interdisciplinary collaboration. Cummings and Kiesler (2005, 2007) find that working across disciplines and working across organizations entails coordination challenges, so to ease the challenges associated with interdisciplinary work, it should be encouraged at individual campuses.

- **Recommendation 5:** Funding agencies can encourage interdisciplinary research by: working with professional associations to encourage cross-disciplinary interaction; being explicit about expectations for interdisciplinary work, and encouraging interdisciplinary team formation at the same university.

But what remains unexamined is whether interdisciplinary collaboration actually results in IDR. Instead of examining interdisciplinary collaboration as an outcome of interest, it may be more useful to view it as an explanatory variable – or at least a mechanism through which other factors reviewed herein (RCs, grad training, funding) may influence IDR. Our review of the literature identified only one study that has done this to date. Basner and colleagues (2013) study center-affiliated cancer researchers using a prospective design to address the question: "Does the cross-disciplinary collaboration affect the type of science generated"? They carefully distinguish interdisciplinary collaboration (which is based on coauthor affiliations) from interdisciplinary scholarship/output (which is based on topics evident in article titles and abstracts; when extracted key terms are associated with both of the two broad fields under study -- Physical Science and Oncology-- the article is considered interdisciplinary). Importantly, Basner and colleagues find that not all interdisciplinary collaborations result in interdisciplinary publications. In fact, just over half do (56%). They find that *intra*disciplinary collaborations also produce IDR, but to a lesser extent, especially in Oncology, where only 24% of intradisciplinary collaborations result in IDR. But the IDR produced by ID teams appeared in the highest impact journals (on average 11.1), slightly above the average impact of IDR produced by disciplinary teams (10.8) and much greater than the average impact of research produced by *intra*disciplinary teams (6.3).

Conclusions

The foregoing synthesis of the literature allowed us to develop five policy recommendations, none of which are mutually exclusive. Indeed, they can be pursued simultaneously, and some can be pursued by multiple actors: policy makers, federal funding agencies, university administrators, and even faculty.

Indeed, coordination across groups and levels might be necessary for effective implementation of many of the recommendations. For example, to support universities' internal seed grant competitions for IDR funding (recommendation #3), funding agencies will have to work closely with university administrators.

While we aimed to provide concrete and specific recommendations, some were necessarily broad. We note that previous research on interdisciplinary graduate training tends to examine more detailed conditions of when and how training can be effective (e.g., when multiple programs co-exist and instill cultural change) on what level of outcomes (e.g. dissertation, post-dissertation), and this allowed us to provide a few concrete and detailed recommendations (like #3 and #5). However, the scholarship on research centers and funding tends to focus a single case or single type of center or grant, rather than examine the types and qualities of those initiatives and whether and how those aspects influence interdisciplinary research. This may be attributable to the general tendency to presume that all RCs are interdisciplinary, and that all (for example) XCUT grants are awarded for interdisciplinary endeavors, though our own research shows these presumptions to be incorrect. Additional research on different types and aspects of centers and grants will allow us to elaborate on the more general policy recommendations we made (like #1 and #4).

Although our report focused on the (often costly) infrastructural aspects of facilitating IDR, we also note some less taxing possibilities that funding agencies can pursue, along with other relevant actors, including professional associations, university administrators, and researchers themselves. First, they can *encourage the integration of disciplines that are somewhat but not too distal.* Research suggests that interdisciplinarity can "go too far:" as the cognitive distance (or dissimilarity) between spanned fields increases, the pay-off in terms of citations declines (Larivière, Haustein and Börner 2015, Yegros-Yegros, Rafols and D'Este 2015). Second, program solicitations and RFAs can *discourage jargon in research proposals.* Vilhena et al. (2014) find that disciplinrary-specific jargon eases communication among colleagues in one's field, it makes communuication across disciplinary bounds much less successful. Third, funding agencies can work with universities and professional associations to *help train scientists and panelists how to review and appreciate IDR efforts.* The work of Michele Lamont and collaborators reveals the challenges of understanding and evaluating interdisciplinary scholarship, and find that reviewers tend to defer to disciplinary experts (Lamont, Mallard and Guetzkow 2006, Lamont 2009). "Research funders clearly have a role to play in framing calls for interdisciplinary proposals and developing rigorous evaluation processes" (Lyall et al. 2013:67).

Unfortunately, the nature of most of the research conducted to date makes it difficult to say exactly which mechanism is most effective for fostering IDR. It is not simply that many studies are case studies, limiting generalizability. It is not simply that most studies are non- or quasi experimental and cross-sectional, and fail to specifically address possible selection effects, thereby reducing internal validity and the ability to make causal conclusions. It is not simply that many studies rely on subjective self-reports, and fail to ensure measurement reliability and validity. Rather, what is lacking is large-scale empirical investigations that not only examine more than a handful of centers, funding programs, or graduate training programs, but which also measure and assess the relative effects of multiple types of mechanisms at once.

SciSIP funding is already beginning to rectify this. In our current grant (SciSIP award #1461989), Sondra Barringer and I are pursuing much of this at the university level. We are collecting data on research centers (and whether they are explicitly interdisciplinary) and on cross-cutting funding efforts via NSF and NIH. We could supplement this with data on interdisciplinary graduate education programs like IGERT and NRT, and with data on university's internal grant mechanisms designed to foster IDR. Steve Brint of UC Riverside (SciSIP award #1736146) is currently collecting data on universities' cluster hiring initiatives, and we've already discussed our shared desire to join data in the near future. Such an effort, while it goes beyond the scope of any currently funded SciSIP project, would allow us to explicitly compare the influence of all of the possible policy mechanisms discussed in this report, and to know which stimulate interdisciplinary scholarship most effectively. It may very well be the case that the causal connection among the mechanisms are quite complex. Funding and cluster hiring may bolster the establishment of research centers and other interdisciplinary units, which in turn bolsters IDR. Or some efforts may interact. For example, perhaps the effect of cross-cutting funding initiatives is amplified in universities in which research centers abound.

A number of interesting new data sources are being combined and developed, and should be capitalized upon to identify the most promising ways to foster IDR. For example, SciSIP and the National Center for Science and Engineering Statistics (NCSES) have been working to connect survey data from PhDs (SED, SDR) with bibliometric data from the Web of Science as well as the USPTO Patent Database. Other initiatives, like the Institute for Innovation and Research on Science (IRIS), are pooling administrative data from member universities and connecting it with university characteristics as well as census data on households and businesses. On their website (http://iris.isr.umich.edu) they state that "much current research on science and innovation is based on hand curated, artisanal, data efforts," which are "designed to answer specific questions [and] are often difficult to use for other purposes, limiting possibilities for use." In response, IRIS is combining detailed and individual level data from universities' administrative records (on student dissertations and on faculty publications, grants, patents) with census data on local demographics, economics conditions, and businesses. With these data, it would be useful to explore whether and how university level characteristics like the ones discussed in this report (research centers, interdisciplinary training programs, funding, and collaboration) promote IDR as manifested in dissertations, publications, and patents.

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