From Sole Investigator to Team Scientist: Trends in the Practice and Study of Research Collaboration

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Abstract

This article reviews trends in the practice and study of research collaboration, focusing on journal publications in academic science. I briefly describe the different styles and types of collaboration and then focus on the drivers of the trend toward increased collaboration and on its consequences for both individual researchers and science more generally. Scholarship on collaboration seems partial to delineating its benefits; this review highlights the increasing body of research that focuses instead on the possible costs of collaboration. The synthesis reveals several topics that are ripe for investigation, including the impact of collaboration on the contributing authors and their work, the use of multiple methods and measures, and research integrity. I applaud a few recent efforts to overcome the perennial file-drawer problem by gaining access to collaborations that do not result in publication and thus are typically removed from public review and the research analyst's eye.

INTRODUCTION

This article is anomalous. Academic research is increasingly social (Powell et al. 2005, Rawlings & McFarland 2011), and this change is most evident in the move away from research produced by individual scientists toward team-based production (West et al. 2013, Wuchty et al. 2007). Indeed, "the lone author has all but disappeared" (Greene 2007, p. 1165). The dramatic rise in scientific collaboration over the twentieth century was termed a "violent transition" in the early 1960s (de Solla Price 1963, p. 79); since then, the shift toward collaboration has continued and perhaps accelerated. Sole-authored works used to dominate science and are still somewhat common in the social sciences; however, today scientists increasingly work with others as part of research teams. Among JSTOR-indexed articles, the prevalence of coauthored articles rose from about 6% in 1900 to over 60% in 2011 (West et al. 2013); among Web of Science–indexed articles, the current prevalence is even greater: 75%. Team size is also growing, averaging 1.9 authors per article in 1955 and 3.5 authors per article in 2000 (Wuchty et al. 2007). These trends hold for patents as well as academic publishing, though this review focuses on the latter.

The trend toward team science is robust and undisputed; it does not depend on the data source or measure. Data on publications indexed in Web of Science (Wuchty et al. 2007), JSTOR (West et al. 2013), and discipline-specific databases like Sociological Abstracts (Hunter & Leahey 2008) all show a rapid rise in collaboration over the last century. The studies mentioned above all rely on the published record and thus on coauthorship to measure collaboration. Although easily available from the archives and capable of capturing key elements of collaboration (Hara et al. 2003), coauthorship data are conservative. They fail to capture more informal collaborations (sharing data, exchanging ideas, helping colleagues learn new techniques; see Lewis et al. 2012) and may also neglect the contributions of students and other assistants, who are not always given coauthor status. Thus, collaboration is more varied, and possibly more common, than the coauthor measures based on bibliometric data sources suggest. Studies that collect data from CVs, which still rely on coauthorship to measure collaboration (e.g., Araújo et al. 2014), and from surveys that allow scientists to define collaboration (Boardman & Corley 2008, Bozeman & Corley 2004, O'Brien 2012) also report rapid increases in collaboration in the past few decades.

Nor is this trend specific to certain disciplines. In 1935, only 11% of sociology articles were coauthored; this increased to over 50% by 2005 (Hunter & Leahey 2008). Wuchty and colleagues (2007) show that the trend for the social sciences mirrors the trend for science and engineering, where the percentage of articles authored by teams rose from 50% in 1955 to over 75% by 2000. The trend continues: In 2010, a whopping 95% of articles published in physics, nanotechnology, and biotechnology were coauthored (Freeman et al. 2015). Collaboration has also been increasing in the life and medical sciences (Parker et al. 2010), economics (Hudson 1996), and astronomy (Milojević 2014). Shrum and colleagues (2007, p. 7) focus on collaborations among scientists at multiple institutions and note that the percentage of articles with coauthors hailing from three or more institutions rose from one-third in 1981 to one-half of all articles worldwide by 1995. Although the focus of Shrum and colleagues is on particle physics—which, like the space sciences, epitomizes "big science" in which articles published by 100+ authors and dozens of institutions are not uncommon—they state that "this trend is evident for every country and every scientific field measured" (Shrum et al. 2007, p. 18), and the similarities across fields outweigh the differences (Shrum et al. 2007, p. 197).

Following the explosion in collaborative activity, studies of collaboration proliferated. In their recent review piece on research collaboration, Bozeman and colleagues (2013) restrict their analysis to articles published since 2000, for a total of over 125 published articles on this topic. This broad interest is understandable. Scientific research is a large part of the economy—accounting for 7% of real GDP growth between 1995 and 2002 (Natl. Sci. Found. 2007)—and collaboration represents a huge shift in the way scientific work is conducted. Science policy experts, in particular, are eager to understand this transformation and to assess its implications. The aim of this review is to identify gaps in this literature and to suggest fruitful avenues for future research. I highlight the contributions that sociologists, in particular, are well suited to make.

WHAT DRIVES COLLABORATION?

Almost every article on collaboration discusses, in its first few pages, the apparent drivers of the trend toward team science. A classic article by Hagstrom (1964) suggests that the cost of scientific facilities and instruments promotes collaborative and often interdisciplinary research efforts. Shrum and colleagues (2007, p. 22) develop a similar argument in their study of particle physics and the space sciences: Collaboration has become more common because "individual organizations cannot command the money, facilities, and expertise needed to acquire the kinds of data their scientists find meaningful." Bennett & Gadlin (2012) suggest that there have been changes in the problems that attract scientists' attention: They are increasingly ill defined, technically complex, and interdisciplinary, requiring expertise in diverse topics. Universities and research centers have actively promoted collaboration among faculty. Policy pushes at the federal level have also been supportive of this trend (Bikard et al. 2015, Clark & Llorens 2012, Cummings & Kiesler 2007, Rawlings et al. 2015): Examples include the Roadmap initiative of the National Institutes of Health (NIH) and the related workshop, titled "Catalyzing Team Science" (Kennedy 2003). Communication technology has been instrumental (Araujo et al. 2014, Binz-Scharf et al. 2015), and travel is cheaper (Katz & Martin 1997). Increasing competition may be partly responsible, too, as scientists aim to work with (rather than against) scientists interested in similar topics.

But perhaps the most oft-cited driver of collaboration is specialization. Science is increasingly complex and specialized, and it is becoming harder for any one person, subfield, or field to comprehensively address a scientific question (Clark & Llorens 2012, Evans 2008, Jones et al. 2008). Some evidence suggests that the increasing specialization in science has directly or indirectly promoted collaboration. Classic studies (Cole & Zuckerman 1975), as well as more recent ones (Moody 2004), have documented a positive relationship between the growth of specialty areas and collaboration rates. As universities have grown and become research intensive, the resultant internal differentiation has often impeded communication among units (Biancani et al. 2014, Friedkin 1978). Increasing specialization and differentiation raise concerns that departments are silos that do not—and indeed cannot—interact with, and stay abreast of developments in, other fields (Brint 2005).

Specialization's impact on collaboration may be attributed to two factors. First, specialty areas are large and highly productive. Thus, it may still be difficult for an individual researcher to digest all the literature in one specialty area, thereby encouraging collaboration with others in that area (Hudson 1996). Second, science that spans boundaries (e.g., subfields, fields) is highly regarded (Natl. Acad. Sci. et al. 2005) and valued by researchers for its novelty and usefulness (Leahey et al. 2015). Although Collins (1986, p. 1355) argues that "the easiest way to establish links among specialized viewpoints is to incorporate them into oneself," most researchers choose to find a collaborator who possesses the expertise that they lack (Boh et al. 2007, Wray 2005). This is wise, because diversity of domain expertise (and approach) enhances problem solving (Page 2007). Because "an individual scientist can seldom provide all the expertise and resources necessary to address complex research problems" (Hara et al. 2003, p. 952), collaborating may be the most efficient way for individuals who only have materials for a partial article to produce a complete article (de Solla Price 1963). Indeed, Leahey (2006) finds that specialization increases scholarly productivity.

Others question specialization as a driving force in collaboration. Beaver & Rosen (1979) argue that professional socialization is critical: After the premodern era, the new way of doing science involved working collaboratively. Because both specialization and professionalization fail to explain variation in collaboration rates across disciplines, the philosopher Wray (2002, p. 163) argues that the availability of—and competition for—financial resources drives collaboration: "Extensive resources make possible elaborate projects which require collaboration." Freeman and colleagues' (2015) analysis, however, suggests that unique knowledge and expertise is a more common reason for choosing coauthors than funding resources.

What is surprising, though, is that there are few empirical assessments of these posited drivers. There are many studies of collaboration, but few explanatory models (Milojević 2014). To date, "no comprehensive theory of scientific collaboration exists" (Shrum et al. 2007, p. 7). Relevant factors can be culled from studies that attempt to explain why individuals choose to collaborate (Melin 2000) and why they continue to collaborate (Dahlander & McFarland 2013), but studies that examine macro-level factors are most useful to understand why collaboration rates are increasing. O'Brien's (2012) analysis identifies some of the mechanisms that prompt greater collaboration rates: the general tendency to collaborate more as one's career progresses, and cohort succession (i.e., younger scholars, who collaborate more early on, replacing retiring scholars). O'Brien (2012, p. 229) wisely distinguishes age and cohort effects, but acknowledges that this only "helps clarify what needs to be explained" and does not provide an explanation in and of itself.

Do we really know why collaboration is increasing? Moody (2004) studied the field of sociology and found that collaboration was more common in more scientific rather than humanistic or interpretive subfields and when quantitative methodologies, which are perhaps easier to divide and delegate, are utilized. Across fields, research methodology also matters: Collaboration is more common in fields like social psychology, because experiments are expensive and time consuming and may require expertise from multiple researchers (Endersby 1996, p. 384). De Solla Price (1986) and, more recently, Clark and Llorens (2012) document the role of research funding. But what about some of the key theorized drivers, like increasing specialization, interdisciplinarity, instrument/technology requirements, and electronic communication? And what about recent changes in the academic labor market, like competition for jobs and increasing publication expectations for hiring and promotion? Answering important questions like these will require the careful compilation of annual panel data from various sources: not just publication archives like Web of Science, JSTOR, or Sociological Abstracts, but also data from universities' human resource departments and promotion and tenure guidelines, academic job banks, National Science Foundation (NSF) award competitions, developments in electronic communication (email, Skype, Dropbox, Google Drive), and the like. Measures of specialization (Leahey 2007) and interdisciplinarity (Porter et al. 2007) exist and could be aggregated to the year or university-year level to support this kind of analysis. Extensive data and measures are regularly compiled for research on social inequality and social policy effectiveness (within and across countries, or even states), but they are regrettably lacking in the world of science policy.

Perhaps because the data requirements are so taxing, a few scholars (largely in information science) have turned to simulation and agent-based modeling to better understand what drives collaboration. Newman (2001) identifies the existence of small worlds (clusters) of scientists in three fields: biomedicine, physics, and computer science. Guimerà and colleagues (2005) empirically and theoretically identify micro-level team assembly mechanisms [number of members, probability of selecting members who already belong to the research network, and propensity of these members to select past (repeat) collaborators] that determine the macro-level collaborative structure of science as well as the success of certain teams. Milojević (2014) constructs simulated team size distributions and validates them with data from 150,000 publications in the field of astronomy to explain how the discipline has changed in the last 50 years. She identifies two modes of knowledge production: core teams, formed by a Poisson process, and extended teams, formed by a power-law process and thus leading to the existence of some extremely large teams.

BENEFITS OF COLLABORATION

Empirical work on collaboration focuses heavily on its beneficial outcomes, possibly because the perceived and real benefits of collaboration contributed to its rise (Wray 2002). There is evidence that collaboration increases productivity. Rawlings and McFarland (2011) find that collaborating increases grant activity (number of submissions as well as number of awards and dollar amount). In terms of publishing, Lee & Bozeman (2005) find that collaborating has a positive effect on a "normal count" of publications (adding more lines to one's CV) but has no effect on a "fractional count" (in which the number of publications is divided by the number of authors). Even if contributing authors do not gain more fractional publications from collaborating (Bikard et al. 2015), they do attain greater visibility on average. Collaborative teams produce more high-impact articles and garner more citations (Fox 1991, Lee & Bozeman 2005, Shi et al. 2009). Wuchty and colleagues (2007, p. 1037) find a "broad tendency for teams to produce more highly cited work than individual authors." Although this could be attributed simply to the greater number of coauthors who can share the work with their diverse sets of contacts (Bikard et al. 2015, p. 7), it could also be attributed to the higher quality of the work that results when people collaborate, bounce ideas off each other, and check each other's work. As Abramo and colleagues (2014, p. 2290) find, "collaborations permit participation in broader research projects, access to funding, and not least, improvement in personal competencies, with positive effects on the quantity and quality of publications." Some scholars have noted that collaboration brings legitimacy to an idea (Bikard et al. 2015); presumably, if more than one scientist believes enough in a project to pursue it, then that project is more worthwhile than sole-authored work that does not have such obvious backing. Although the benefits of collaboration vary by discipline (Walsh & Bayma 1996), in general collaboration ensures funding flows and career advancement (Abramo et al. 2014, Jeong & Choi 2015). Clearly, collaboration is beneficial for individual scientists (Presser 1980) and perhaps for scientific progress more generally (Hara et al. 2003).

COSTS OF COLLABORATION

One of the more promising and sociologically minded developments in this literature is the increasing recognition (and investigation) of the costs of collaboration, which begins to balance the heavy focus on benefits. Cummings & Kiesler (2005, 2007) and Shrum and colleagues (2007) have documented the communication and coordination costs that accompany collaboration, especially collaborations that cross disciplinary and/or institutional bounds. Often, the goals of team members are not aligned, communication is difficult because team members lack a common language and set of experiences, and translation is needed. Moreover, processes and routines need to be developed so that work can be distributed and synchronized and progress can be monitored effectively (Bikard et al. 2015). Such articulation work (Fujimura 1996)—managing people, maintaining hardware and software and material supplies, communicating with coauthors, and updating funding agencies via reports—falls on the head of a laboratory scientist and draws him or her away from the actual research (Hackett 2005). It is possible that these additional administrative tasks compromise real productivity. As noted earlier, collaborating allows one to publish more articles (so there will be more lines on one's CV; see Crane 1972, Lee & Bozeman 2005), but fractional productivity (toward which sole-authored articles contribute 1, articles with two authors contribute 0.5, articles with three authors contribute 0.33, etc.) is not bolstered and indeed may decline (Bikard et al. 2015, Lee & Bozeman 2005). Thus, the "coordination difficulties stemming from collaboration in creative work are generally associated with a loss of individual productivity" (Bikard et al. 2015, p. 6). Presumably, because (at least for promotion and tenure purposes) all citations of an article are credited to all coauthors, reduced productivity is offset by enhanced visibility (Bikard et al. 2015).

A few scholars in particular have conducted in-depth investigations of the potential costs and tensions inherent in collaboration by conducting interviews with team leaders and members. Boardman & Bozeman (2007) highlight the role strain that besets scientists engaging in collaboration via research centers. These individuals are subject to competing demands in the workplace, and this can take a toll on their job satisfaction, productivity, and emotional well-being. Whereas these competing demands results largely from distinct organizational allegiances (e.g., to one's department or research center) and from the centers' foci on interdisciplinary work and technology transfer (both of which require domain spanning), it is likely that role strain accompanies scholars in more general types of collaborations, too, as they figure out how to balance an independent research program with collaborative work, as well as in multiple collaborations. Hackett (2005) identifies this tension between independence and dependence and also explores other polarities, including cooperation/competition, openness/secrecy, democracy/autocracy, and risk/control in his study of molecular biology labs. Through an in-depth case study of one collaborative team in ecology, Parker & Hackett (2012, p. 21) identify the emotional work that, while enhancing creativity, also make skepticism "more likely to occur and more challenging to manage." Initial collaborative success prompts growth in the size and diversity of the team, but these changes endanger the conditions that prompted success in the first place, producing yet more tensions in collaborative work. McBee & Leahey (2016) identify numerous challenges faced by even the most successful interdisciplinary humanities scholars, including a lack of formal and informal support, dampened productivity, and devaluation in the peer-review process.

Another cost of collaboration is free riding: Some coauthors do not do much (or any) of the work but are still included as coauthors. How common are guest authors whose names appear in the list of authors, but who in reality contributed very little to the article? We do not know; the evidence is largely anecdotal. Empirical research—probably at the team level, and probably qualitative—is needed to ascertain the prevalence of this practice in scientific research. In an effort to stymie the inclusion of guest authors, some top journals (e.g., Nature, Science, PNAS) have encouraged authors to delineate how each author contributed to the article. However, this practice remains rare. It would be interesting to track the diffusion of this practice across journals and disciplines; according to Endersby (1996, p. 390), "the ideal standard for attribution of credit may be to footnote each author's responsibilities and percentage of credit for published research." Regardless of individual practice and emerging journal policy, the American Sociological Association Code of Ethics stipulates that: (*a*) "Sociologists take responsibility and credit, including authorship credit, only for work they have actually performed or to which they have contributed"; and (*b*) "Sociologists ensure that principal authorship and other publication credits are based on the relative scientific or professional contributions of the individuals involved, regardless of their status. In claiming or determining the ordering of authorship, sociologists seek to reflect accurately the contributions of main participants in the research and writing process" (see **http://www.asanet.org/images/asa/docs/pdf/CodeofEthics.pdf**).

Another underdeveloped concern with collaboration is potential exploitation. At least two studies of types of collaboration have found evidence of advisor-advisee collaborations, which "raise many particularly sensitive issues" (Endersby 1996, p. 385). Leahey & Reikowsky (2008) identify a "mentoring" style of collaboration, wherein established scholars join with scholars-in-training to publish research together; this style characterized about 10% of the sociology articles they sampled. Their supplementary interview data suggest that this collaborative style is on the rise due to job market and tenure expectations for productivity. As one interviewee stated, "We've become more generous as a discipline and we're more willing to give graduate students the opportunity to collaborate" (Leahey & Reikowsky 2008, p. 435). Bozeman & Corley's (2004) principal components analysis of survey data from a sample of 1,000 scientists also found a mentoring style of collaboration to be common among scholars who desire to help junior colleagues and graduate students. They do not provide a sense of how common this style is, but they do indicate that mentors are more open to industry collaboration and tend to collaborate with graduate students and junior colleagues who are women. Collaborating with students and junior colleagues in publishing is one of the most helpful things an advisor can do (Long & McGinness 1981), and research documents that women are not only more likely to collaborate than men (Abramo et al. 2013, 2014), but they are also more likely to benefit, in terms of productivity, from it (Kyvik & Teigen 1996). Hu and colleagues (2014) find that senior faculty benefit more from collaborating than junior faculty. Thus, it appears that the potential for exploitation lies not in women's and younger scholars' contributions being neglected completely (indeed, they are listed as authors), but in the fact that they might not receive appropriate credit [i.e., they do most of the work but are listed only as contributing, not lead, authors (Larivière et al. 2015b)]; and even if they are the lead authors, audiences may associate the article with the senior author's name, to the detriment of the junior scholars' visibility.

This begs the important question of credit allocation. With increasing collaboration, new approaches to evaluation will be necessary. This is especially true in academia, in which individual reputation is paramount (Whitley 2000). As Freeman and colleagues (2015, p. 42) note, "arguably the biggest problems collaborations must solve in order to succeed is to find ways to divide the credit." As Hagstrom (1964, p. 253) noted in the 1960s, "individuals become anonymous in large groups; talents of individual cannot be easily judged." Order of authorship, though typically indicative of the relative contributions of each author (i.e., who did more than whom), does not indicate how much more some authors did, nor how the labor was divided. Currently, evaluation and promotion and tenure committees rely heavily on letters of reference to ascertain this information. However, relying "on the word of superordinates and others on the research team reduces the independence of the individual" (Hagstrom 1964, p. 253). A more complex credit allocation system is necessary (Bikard et al. 2015, p. 6), one that goes beyond the general principles outlined in ethics codes and provides details in an explicit and public way. This is where journal policy can really help shape practice.

An important and broad implication of increasing collaboration is that inequality is intensifying, at least at the individual and institutional levels.[1] In their study of 4.2 million articles published between 1975 and 2005, Jones et al. (2008, p. 1261) find that scientists are selecting coauthors across universities, but not across university prestige levels. Scientists at elite universities are more likely to collaborate with scientists at other elite universities, and the same homophilous tendency is seen among scientists at nonelite universities. Jones and colleagues conclude that social distance is becoming more important, just as geographic distance is becoming less important. Moreover, because multi-university publications have a higher impact relative to articles published by scholars at a single university, and researchers at elite universities are more likely to engage in such multi-university collaborations, the production of outstanding scientific knowledge is increasingly concentrated (Jones et al. 2008, p. 1261). The diffusion of scientific knowledge is

[1]Xie (2014) suggests that globalization and the Internet have reduced inequality among countries.

also increasingly concentrated. In their study of Stanford faculty from 1997 to 2006, Rawlings and colleagues (2015) find that although more faculty are receiving knowledge from fellow faculty (i.e., adopting references from a fellow faculty member's published references), fewer are responsible for sending knowledge: The proportion of faculty sending knowledge declined from 61% in 1997 to 44% in 2006. "Star" scholars, who are more likely to be the sources of knowledge flows (Rawlings et al. 2015), also improve the quality and quantity of their collaborators' productivity (Azoulay et al. 2010). The sources of knowledge are becoming increasingly concentrated (Evans 2008) even in this interdisciplinary era.

Will these costs increase and possibly slow the trend toward team science? Probably not. Hackett (2005) and Murray (2010) show how tensions can be creative and advance the work to be done, especially if they are addressed productively and wisely. However, the identification of the costs of collaboration has certainly spurred efforts to mitigate them. Funding agencies support collaborative efforts financially. A prominent example is the NIH's Roadmap for Medical Research, launched in 2004 to transform the way biomedical research is conducted by fostering high-risk/high-reward research, enabling the development of transformative tools and techniques, filling knowledge gaps, and changing academic culture to foster collaboration. Universities are doing the same with internal funding mechanisms. Research administrators are also establishing research centers to enhance communication and reduce physical barriers to interaction (Boardman & Ponomariov 2014, Dahlander & McFarland 2013, Kabo et al. 2014), fostering mentoring and training programs within and across departments (Hackett & Rhoten 2009), and revising standards for the evaluation of interdisciplinary scholars (Boix Mansilla 2006). Moreover, the newly formed research community Science of Team Science is actively studying the elements of effective teams (Bennett & Gadlin 2012, Cooke & Hilton 2015, Stokols et al. 2008). Trust is a critical component of collaborative research (Shapin 1994, Shrum et al. 2007), as is face-to-face interaction (Hampton & Parker 2011) and a shared cognitive–emotional–interactional platform (Boix Mansilla et al. 2016), particularly for interdisciplinary collaborations.

There are several ways in which individual scientists can mitigate the costs of collaboration. They may, for example, engage in repeat collaborations by working on projects and publishing with the same set (or subset) of authors repeatedly. As Dahlander & McFarland (2013, pp. 69–70) detail, repeat collaborations have "fewer startup costs than new ones, they entail greater certainty and trust," and collaborators communicate better; this prompts "easier and more effective communication" and more "reciprocal forms of exchange." They also find that repeat collaboration (what they call persistent ties) offers greater returns on the rate of productivity and performance quality [although Inoue & Liu (2015) find that innovation can suffer, at least with respect to patents]. Individual scientists may also collaborate with like-minded others who share areas of expertise, methodological approaches, or theoretical perspectives. As elaborated in the next section, such a reinforcing style of collaboration likely improves efficiency and productivity because "returns to the time spent on tasks are usually greater to workers who concentrate on a narrower range of skills" (Becker & Murphy 1992, p. 1137). It also suggests that "sticking with one's own" is a viable and common strategy in this age of what some call hyperspecialization and fractionalization (Collins 1986, Davis 2001). When coauthors share areas of expertise, the typical costs of collaboration (e.g., coordination, control, different motives; see Shrum et al. 2007) are mitigated: Epistemological divides (Knorr Cetina 1999) are rare, shared understandings are easier to achieve (Lamont 2009), and efficient and exploitative search strategies are possible (March 1991). All of these reduce uncertainty and foster confidence in predictable and positive outcomes. And lastly, individual scientists may choose to work closer to home in terms of not only intellectual space but also geographic space, and thereby reduce or eliminate concerns about distance, lack of interaction, time zone differences, and the like—because distance still matters (Kabo et al. 2014, Olsen & Olsen 2000).

However, such reliable "succession" (Bourdieu 1975, p. 30) also has drawbacks. Namely, it does not foster broad exploration, the pooling of diverse ideas, and the development of innovative, creative ideas (Hargadon 2002, Weitzman 1998). It rarely pushes the boundaries of science in new and fruitful ways, and it may not be conducive to scientific breakthroughs and transformative science. The highest-impact collaborations are those that reach across domains, like disciplines, institutions, and countries (Bikard et al. 2015, Larivière et al. 2015a, Leahey et al. 2015, Uzzi et al. 2013), and when scientists work to mitigate the costs of collaboration, they may also be sacrificing or at least tempering these potential gains. Although collaborations between complementary specialists are rare in the field of sociology, representing only 11% of articles (Leahey & Reikowsky 2008), these boundary-spanning collaborations are especially fruitful (Leahey & Moody 2014). Again we see trade-offs.

Although scholarship on different types of collaboration, reviewed next, is plentiful, researchers are just beginning to examine whether and how the costs and benefits of collaboration vary across such types.

TYPES OF COLLABORATION

As mentioned earlier, a few studies have delineated general styles of collaboration (Bozeman & Corley 2004, Hara et al. 2003, Leahey & Reikowsky 2008). Although it is common to view collaboration in opposition to a scientific norm of individualism (Hackett 2005, Merton 1973a), at least one prevalent style of collaboration is consistent with the norm of individualism. Collaborative research that reinforces (Leahey & Reikowsky 2008) and consolidates (Foster et al. 2015) known areas of expertise is, arguably, an extension of sole-authored research. This style of collaboration, in which coauthors' knowledge domains overlap considerably, is common in sociology (Hunter & Leahey 2008) and in biomedical chemistry, where repeat consolidations far outnumber the exploration of new chemicals and relationships (Foster et al. 2015). Of all coauthored articles in Leahey & Moody's (2014) sample of sociology articles, 80% fall into a single specialty area. Clearly, a large proportion of research today is focused on depth: Scholars join together with others who share their area(s) of expertise and produce work that contributes to a single research area.

Another style of collaboration aims to complement and extend. Leahey & Reikowsky's (2008) research finds that complementary specialists and generalists broaching a new topic are rare in the field of sociology, representing 11% and 18% of the sampled articles, respectively. But these collaborative styles illuminate the bright side of increasing specialization in science: They encourage a branching out, whether through finding a fellow specialist with different but complementary interests or by moving forward to a new topic area—via accretion, substitution, or migration (Gieryn 1978). These domain-spanning collaborations tend to have higher impact in terms of citations (Leahey & Moody 2014, Uzzi et al. 2013).

A mentoring style of collaboration has been identified by Bozeman & Corley (2004) and Leahey & Reikowsky (2008). Hara and colleagues (2003) identify two subtypes: collaboration with students (which involves mentoring, close contact, and joint productions) and collaboration through students (wherein students work with, and thereby link, two or more faculty members). The close collaboration that takes place between mentors and their students also tends to be reinforcing, as students often take up a subset of their mentors' research programs (Bozeman & Corley 2004, Crane 1969, Mullins 1983).

In addition to these general styles of collaborative work, collaboration can also occur across nations, domains of science (public and private), universities, and disciplines. International collaboration (in which the coauthors hail from two or more countries) is increasingly common. As Xie & Killewald (2012, p. 28) determine from NSF indicators, "worldwide, between 1988 and 2005, the share of publications with authors from multiple countries increased from 8% to 20%." Some of this is likely attributable to the growth of higher education and scientific investments in formerly less developed countries like China (Xie et al. 2014). Moreover, research teams with authors hailing from four or more countries are the fastest growing mode of scholarship (Hsiehchen et al. 2015). International collaboration is particularly beneficial in terms of visibility; it also presents some unique problems due to differences in language, technology, time zone, and professional norms regarding research integrity and human subjects (Duque et al. 2005, Freeman 2014, Jeong et al. 2014).

Collaboration across scientific domains (between scientists based in universities and scientists based in for- and non-profit organizations) is also proliferating. No doubt this stems partly from encouragement and funding from federal agencies, like NSF's support of Industry/University Collaborative Research Centers that engage in research of interest to both domains. University scientists become involved with private, commercial science in multiple ways: through patenting, licensing, firm founding, consulting, and serving on scientific advisory boards (Colyvas & Powell 2007, p. 233; Etzkowitz et al. 1998; Luo et al. 2009; Owen-Smith 2005a; Powell et al. 1996; Zucker & Darby 1996; Zucker et al. 2002; Stuart & Ding 2006). Not only the variety but also the intensity of university-industry relations expanded since the passage of the Bayh-Dole Act in 1980, which allowed universities to retain intellectual property rights over ideas developed with the support of federal funding (Owen-Smith 2005b). Smith-Doerr & Vardi (2015) explore how these domains come together by examining collaboration among chemists, with a focus on the ethical aspects of scientific practice.

Cross-university collaboration is yet another type of collaboration on the rise (Jones et al. 2008). Shrum and colleagues (2007) identify data, technology, and instrument needs as a key driver of this type of collaboration. Cummings & Kiesler (2005, 2007) document the benefits and especially the costs associated with this type of collaboration (see also Boh et al. 2007).

Collaboration across disciplines has received much attention, both from scholars and from policy-oriented analysts. As Hackett & Rhoten (2009, p. 409) summarize, the integration (or synthesis) of ideas, methods, and data from distinct disciplines has been a transformative force in science, one that has attracted policy interventions, program innovations, and financial resources. This is evident from the recent enthusiasm for mixed methods research (Leahey 2007), interdisciplinarity (Natl. Acad. Sci. et al. 2005), and synthesis (Parker & Hackett 2012), as well as the emergence of cross-cutting funding initiatives (like NSF's CREATIV and INSPIRE)[2] and the proliferation of fellowship programs hospitable to interdisciplinarity (Lamont 2009) and explicitly supportive of it (e.g., the Radcliffe Institute for Advanced Study at Harvard). Available external and internal funding is increasingly restricted to multidisciplinary teams (Sá 2008). Interdisciplinarity has become "synonymous with all things progressive about research and education" (Rhoten & Parker 2004). In a recent article, Boix Mansilla and colleagues (2016) identify the shared cognitive–emotional–interactional aspects of successful interdisciplinary collaborations.

A few researchers are pushing the study of interdisciplinary collaboration forward by moving beyond binary measures. Most investigations of domain spanning simply assess whether boundary spanning has occurred (Clemens et al. 1995, Fleming et al. 2007); this is done by examining

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

the subfields or fields that are represented by an article, its references, or its authors. However, consideration of the novelty of the pairing is critical for elucidating processes of innovation. Only a few scholars have empirically assessed the uniqueness, or rarity, of combinations (Braun & Schubert 2003, Leahey et al. 2015, Uzzi et al. 2013). Porter and colleagues (2007) have developed a measure of domain integration that incorporates the relationships between domains: Are they paired frequently in the literature, or rarely? This is ideal because it is new connections (not common ones) that help define originality (Guetzkow et al. 2004). The most fertile creative products are "drawn from domains that are far apart" (Poincaré 1952, p. 24), and the best conceptual metaphors are those that create ties across great distances (Knorr Cetina 1980). Put simply, integrative work can be more or less innovative, depending on the relationship between the integrated entities (Carnabuci & Bruggerman 2009, p. 608). For most analyses, it is possible to examine not only whether two domains are spanned, but also how rarely they are spanned, which provides an indication of the novelty of the pairing. Evans (2016) at Stanford is incorporating all these considerations, and more, as she develops a measure of interdisciplinarity that is based on a comparison of scholars' texts (titles and abstracts) to various disciplinary corpora.

A fruitful avenue in recent research is to explore whether and how the benefits of collaboration depend upon the nature of the collaboration. Research in this vein finds that benefits are most pronounced when collaboration occurs across subfields (Leahey & Moody 2014), departments (Bikard et al. 2015, p. 23), and disciplines (Leahey et al. 2015), especially those that are more cognitively distant (Larivière et al. 2015a, Uzzi et al. 2013). Collaboration can "increase explanatory coherence" and produce "conceptual combinations that establish new theoretical frameworks" (Wray 2002, pp. 156–57), especially when it involves scientists trained in different disciplines. International collaborations are more productive and result in more citations than collaborations among researchers from a single country (Freeman 2014, Jeong et al. 2014). Other research has found that benefits are tempered when junior scientists team with more senior scientists (Heffner 1979). Social network analyses are illuminating just which types of connections are most beneficial (Fleming et al. 2007, Ghosh et al. 2015, Reagans & McEvily 2003, Wang & Hicks 2015). For example, Ahuja (2000) shows that weak ties that constitute structural holes may be ideal for transferring information, but their lack of trust hinders the transfer of know-how.

The costs of collaboration may also depend on the type of collaboration. Bikard and colleagues (2015, p. 24) find that costs are actually lower for cross-departmental work that takes place within the same university. Cummings & Kiesler (2005, 2007) find that communication and coordination costs are pronounced in collaborations that span universities and disciplines. Because interdisciplinary research is a high-risk, high-reward endeavor, the benefits as well as the costs may be heightened for this type of collaboration. Leahey and colleagues (2015) find this to be the case: Scholars engaging in interdisciplinary research experience heightened visibility, as measured by citations, but damped productivity. Costs may be especially pronounced for early-career scholars and graduate students. In their study of five NSF-funded environmental programs, Rhoten & Parker (2004) found that graduate students demonstrated higher rates of interdisciplinarity than professors (62% compared to 49%). But graduate students were also more likely to recognize the potential risks of pursuing an interdisciplinary path, such as the longer time spent getting established in one's career and known in one's field. Young scientists in training feel the "tension between the scientific promise of the interdisciplinary path and the academic prospect of the tenure track" (Rhoten and Parker 2004, p. 2046). Although interdisciplinary centers and training program are springing up and offering graduate students opportunities to experience cutting-edge research and cross-fertilization, employers still prefer to hire scientists who have stayed in established disciplines (Nelson 2011). This and other drawbacks of interdisciplinarity are elaborated in Jacobs & Frickel (2009) and McBee & Leahey (2016).

Because the types of collaboration are not mutually exclusive (authors can hail from both different countries and disciplines, for example), identifying the costs and benefits of different collaborative combinations may be challenging. Science of Team Science scholars are studying the effectiveness of different types of small research groups to understand just these distinctions (Falk-Krzesinski et al. 2010, 2011; Fiore 2008; Stokols et al. 2008).

As we have seen, scholarship on the benefits (and increasingly, the costs) of collaboration and on the different types of collaboration has been plentiful. In other arenas, however, progress has been less extensive. The remainder of this review focuses on these gaps in the literature and identifies fruitful avenues for future research.

SELECTION BIAS

The quantitative scholarship on research collaboration relies heavily on the published record available through Web of Science (Wuchty et al. 2007), JSTOR (West et al. 2013), and disciplinary databases like Sociological Abstracts (Hunter & Leahey 2008, Leahey & Reikowsky 2008, Moody 2004), which raises concerns about the role of selection bias. Especially when the benefits of collaboration (e.g., increased citations, impact, visibility) are documented, one can only wonder whether this is attributable to unsuccessful projects going unobserved—that is, not published or otherwise brought into the public domain of science. It is likely that the collaborative projects that are actually observed "reflect the highest quality among those projects" (Bikard et al. 2015, p. 8). It is common for scholars relying on the public record to note this limitation (e.g., Lee et al. 2015, p. 695), but it is less common for scholars to address it. Cummings & Kiesler (2007) do so in their study of multi-university research projects: Their main analysis focuses on funded projects, but they take pains to collect data on unfunded projects and discover that selection bias partly explains the association between multi-university projects and poor project outcomes. NSF proposals including more universities were not as exemplary as proposals from a single university, but they were more likely to be selected for funding, given the mission to fund multi-university projects. Leahey and colleagues (2015) include a subanalysis of unpublished working articles in their analysis of collaborative scientific research; Li (2016) obtained access to both funded and unfunded NIH proposals written by research teams to assess peer reviewers' expertise and potential bias. Hara and colleagues (2003) intentionally studied teams that were constructed organically as well as a team that was administratively assigned. Their insights from this one negative case (in which collaboration did not emerge organically) carried over to the others and allowed them to identify factors that ease collaboration, like socio-technical infrastructure and compatibility.

IMPACT ON CONTRIBUTORS

Only a few recent studies have begun to investigate how collaboration itself alters and reshapes the works (and workers) that were originally joined. In his ethnographic study of meteorologists, Barley (2015, p. 1625) finds that "experts shape their own work practices to produce outputs that can bridge boundaries." In anticipation of sharing their work in the form of visual representations with others, meteorologists "modified their disciplinary work so they could produce outputs that would be representable." Thus, the idea itself of collaborating and sharing knowledge alters the nature of work that is conducted. Another brilliant study by Rawlings & McFarland (2011) examines how the act of collaborating with one person or group alters a researcher's knowledge stock. They assess this by developing a creative measure of scholarly influence, which assesses changes in Scholar A's published bibliographies before and after collaborating with Scholar B to see if the new references in Scholar A's bibliographies were present in previous work by Scholar B. Murray (2010) extends this focus to the distinct (but merging) worlds of science and commerce, whose distinct logics typically create tension. She deems it critical to investigate the meaning that hybrids have for the two worlds. Murray's analysis of a landmark case at the industry-university divide—DuPont's exclusive license to Harvard's patented OncoMouse (a mouse genetically engineered for use in cancer studies)—shows that meaning matters:

> Scientists changed the traditional meaning of patents and incorporated them into hybrid exchanges at the boundary as a means of maintaining (and even strengthening) the distinction between academic and commercial logics. Consequently, while patents changed the boundary between academia and commerce, scientists' boundary work changed patents. . .and produced hybrids that maintained the two worlds in productive tension. (Murray 2010, p. 346)

Hackett and colleagues (2004) focus on research technologies in fusion energy research and find that such ensembles influence the research of team members—sometimes positively and sometimes negatively, depending on team characteristics. These three studies are exemplary and will ideally spur additional research on how collaboration alters the original contributing work.

MULTIPLE METHODS AND MEASURES

Surprisingly few studies incorporate more than one method or measure. Numerous studies of collaboration rely on data collected from secondary sources like the Web of Science (Wuchty et al. 2007), JSTOR (West et al. 2013), or Sociological Abstracts (Moody 2004), which allow researchers to obtain limited data on a large sample, or the entire population, of published research articles. Other studies have turned to scientists' CVs to obtain data (Araújo et al. 2014). A few other studies collect data from primary surveys (Boardman & Corley 2008, Bozeman & Corley 2004, O'Brien 2012) or interviews (Lewis et al. 2012), which allow researchers to obtain in-depth data on a more limited sample and to measure collaboration more broadly (i.e., not limited to the authorship of published articles).

Mixing these data types, and the measures they allow, might be best for understanding how and why collaboration has been increasing so rapidly. Thorsteinsdóttir (2000), Freeman and colleagues (2015), and Qin and colleagues (1997) joined bibliometric data from the Web of Science with interviews and surveys of authors to understand their motivations for collaborating, including their desire to gain access to materials—something that could not be gleaned from bibliometric data alone. Other scholars have pooled data from various sources, including physical maps of authors' work locations, when studying one or a few research organizations in depth (e.g., Kabo et al. 2014). With institutional backing, sociologists Dan McFarland, Craig Rawlings, and colleagues have collected vast amounts of data on all Stanford faculty from CVs, Web of Science, and Stanford's human resources and institutional research departments. These rich longitudinal data have allowed them to measure multiple connections among faculty (e.g., dissertation committees, coinvestigator status on a grant, coauthorship, shared research center affiliation, shared department) and to dive deeply into the process of knowledge diffusion on campus (Biancani et al. 2014, Dahlander & McFarland 2013, Rawlings & McFarland 2011, Rawlings et al. 2015).

RESEARCH INTEGRITY

Especially given recent cases of research misconduct in the social sciences, and the Office of Research Integrity's interest in funding studies of misconduct, the time seems ripe to investigate whether and how collaboration promotes, or possibly detracts from, research integrity. As noted earlier, there has been substantial interest in credit allocation and authorship rights (Biagioli 2003), but blame allocation (when things go wrong) and authorship responsibilities are often overlooked.

Wray (2002) notes the diffusion of responsibility that accompanies collaboration: Who should get credit, and how much? But also, when things go wrong, who should be blamed? The success of science in reputational work organizations like academia (Whitley 2000) depends on scientists' getting credit when it is deserved and losing credibility when blame is deserved (Hull 1988, Merton 1973a): "A scientist gets credit, but has to take epistemological (and perhaps legal) responsibility for the truth of the claims he or she publishes" (Biagioli 2003, p. 256). One benefit of a journal policy that requires authors to delineate their unique contributions to an article is that when errors are found, a responsible person (or persons) can be identified. However, Galison (2003, pp. 352–53) notes the tension between "the desire to recognize justly the distributed character of the knowledge essential to any demonstration" and the "desire to make scientific knowledge the issue of a single conscious mind." Because

> when the question is asked, "Who did this work, that is, who is in command of this particular analysis and all on which it depends?"—the answer must always be deferred. It is entirely possible, even likely, that no one individual (much less a group of individuals) is entirely in control over the full spectrum of justificatory arguments that feed all the way down into the guts of the. . .analysis code. . .and methods. (Galison 2003, p. 352)

Kennedy (2003), former editor-in-chief of *Science*, argues that one should know his or her collaborators well enough to trust their work, and that therefore all coauthors should accept credit as well as blame when it is due. However, the prevalence and stability of this view may vary across fields, time, and types of collaboration, and this variation provides a useful object for future analysis. For example, Youtie & Bozeman (2014, p. 658) find that negative coauthorship experiences are more likely as team size grows.

Beyond authorship and credit/blame allocation, collaboration likely influences other aspects of research integrity, many of which have yet to be investigated systematically. Smith-Doerr & Vardi (2015) provide a much-needed qualitative look at the ways in which research ethics requirements and policies are interpreted and met in practice by chemists working collaboratively in both academic and industrial settings. Wray (2002) contends that collaborative research helps to prevent previous discoveries from being forgotten. He recalls Merton's (1973b, p. 408) identification of some "nearly lost" discoveries; however, "if some members of the team forget them, others will not. Moreover, repeated interaction between collaborators will tend to fix these ideas and findings in memory." If the division of labor is not too stark, and a system of review and checks and balances is in place (as it ideally is in large collaborative projects), then collaboration may also enhance quality control and prevent fraud. Collaboration is likely good for catching errors (Clark & Llorens 2012) and for identifying and filtering out bad ideas before they come to fruition (Bikard et al. 2015, Singh & Fleming 2010). For various reasons—not the least of which is the large team size—particle physics, astrophysics, and observational cosmology have not been caught up in scandals of fraud. Indeed, Galison (2003, p. 350) states, "I do not know of a single instance in high-energy physics where fraud, fabrication, or authentification of authorship became a pressing issue."

CONCLUSION

Since collaboration has become normative in scientific fields, studies of collaboration in its various forms as well as of the causes and implications of the trend toward collaboration have proliferated. Yet much work remains to be done. With respect to the forms of collaboration, we might begin by acknowledging the overlapping and multiplex form that most collaborations take: For example, they are interdisciplinary and international. We can also begin to assess how the benefits and costs of collaboration vary across these types. It would behoove scholars to devote more time to studying collaborations that do not result in coauthorship (Lewis et al. 2012), especially the common but rarely studied acknowledgments in scholarly articles. One reasonable expectation may be that as scholars age professionally and become more entrenched in their scholarly community, their own coauthored articles may decline, but their informal support and mentoring of others (particularly junior scholars), as indicated in the acknowledgments, may increase. With respect to the causes of collaboration, studies of individual motivations to pursue collaboration have outnumbered macro-level explanations of the increasing rates of collaboration, which require intensive and extensive data compilation that NSF would likely be eager to fund. Systematic attention should also be paid to the role of technology. Without computer technology (the Internet, Skype, document-sharing programs, coediting software), collaboration (particularly across institutions and geographic boundaries) would have remained minimal in spite of increased specialization (Hunter & Leahey 2008) and funding availability. Technology is also permitting researchers to access new kinds of data and to leverage greater amounts of data to help answer important science policy questions. With respect to the implications of collaboration, studies have focused largely on (article) productivity and visibility as measured by article citations or journal impact. A few of them claim to measure collaboration's impact on innovation but only measure performance (typically in the form of citations). One promising direction is taken by Lee and colleagues (2015), who develop a way to unpack novelty and impact. The data and the theory exist to support analyses of how collaboration in its various forms influences innovation and novelty: that is, the pairing of unlikely combinations that are indeed fruitful. The work of Uzzi and colleagues (2013) and Funk & Owen-Smith (2016) is foundational in this regard.

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Errata

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