A REVIEW OF ECONOMIC PERSPECTIVES ON COLLABORATION IN SCIENCE

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I. Introduction

This paper provides a review of economic perspective on collaboration in science (or team science).[1] It aims to explain two central facts about scientific collaboration: First, it identifies a series of explanations regarding the factors drawing together scientific collaborators. Second, it addresses the most salient empirical fact about scientific collaboration over the past century, asking why the fraction of scientific projects undertaken by teams and why the size of such teams has been growing over time (Jones, Wuchty and Uzzi, 2008; Wuchty, Jones and Uzzi, 2007; Adams, eta al., 2005).

A variety of approaches within the economics of science address issues of scientific collaboration. We do not, therefore, advance the idea that a single perspective unites these approaches or that a canonical way of thinking about team science has emerged. We should also note that economic approaches to collaboration build quite directly on approaches in sociology, particularly the work of Robert Merton (), and complementary approaches in other fields, including psychology and organizational theory (Dasgupta and David, 1994). We highlight such work in a number of places below, noting its foundational influence on the economics-oriented papers we review. We begin, though, by noting three distinctive features of the economics of science upon which our literature review builds.

First, we note that a tradition of research in the economics of science focuses on the role of knowledge accumulation. This view explains itself most simply by appealing to Newton's famous quotation that if he has seen further, it is because he has stood on "ye

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[1] In this review, we will use the terms "collaboration" and "team science" interchangeably.

sholders of giants."[2] This perspective views the accretion of scientific and technical knowledge as central to economic growth and considers this to be a fact understood in at least some form since the development of scientific societies and related research institutions in the 17th century. In perceiving knowledge as cumulative and as essential to productivity growth, economic growth, and the progress of social welfare, this view differs fundamentally from perspectives that emphasize the social construction of knowledge (Berger and Luckman, 1966) or that suggest that knowledge proceeds through patterns of paradigmatic shifts (Kuhn, 1962) that do not suggest progressive understanding as a core feature of the research enterprise.

This view has been influential in a number of areas of economics, including in macroeconomic models of ideas-driven (or endogenous) growth which postulates that a knowledge generating segment of the economy drives knowledge accumulation, which is essential for warding off diminishing returns and ensuring economic growth (Romer, 1990; Grossman and Helpman, 1991; Aghion and Howitt, 1992; Jones, 1995) and in microeconomic (industry-level or scientific field-level) models of step-by-step technical progress (Scotchmer, 1991; Gallini and Scotchmer, 2002; Aghion et al., 2008). These models often abstract away from the details or microfoundations of knowledge accumulation; however, related views building on economic history focus on mechanisms by which knowledge can accumulate, noting that institutions and policy help preserve knowledge, communicate knowledge over time, and ensure that researchers can access geographically distant or temporally distant research, ideally, at low costs (Mokyr, 2002;

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[2] Isaac Newton famously acknowledged the importance of cumulative research in a 1676 letter to rival Robert Hooke: "What Des-Cartes did was a good step. You have added much several ways, & especially in taking ye colours of thin plates unto philosophical consideration. If I have seen further it is by standing on ye sholders of Giants" (quoted in Stephen Inwood, 2003, pp. 216).

Rosenberg, 1963). Increasingly, empirical work is also elucidating the specific institutions and policies that support such knowledge accumulation (e.g., Furman and Stern, 2011; Furman, Murray, and Stern, 2012; Agrawal and Goldfarb, 2009; Rysman and Simcoe, 2008).

A second feature of our perspective is that it regards science as a competitive enterprise in which scientists have varied, sometimes competing goals. Merton's ideal-typical vision of scientists' aims highlights the search for fundamental knowledge, freedom to pursue research topics and approaches, rewards driven in great measure by peer communities, and the open diffusion of research results (1973). Empirical work on these topics provides supporting evidence, including one particularly creative study that demonstrates that budding industrial scientists will tradeoff substantial levels of potential salary in exchange for the ability to use firm time and resources to pursue scientists' own research agendas (Stern, 2004). A range of research on scientists' behavioral patterns, including comparisons of academic and industrial scientists (Sauermann and Stephan, 2013) and reviews of scientist sharing behaviors (Häussler et al., 2013) suggest that scientists' motivations vary from the Mertonian ideas. Indeed, Stephan (2012) devotes an entire chapter in her book, *How Economics Shapes Science,* to a discussion of the role of money in shaping the behavior of scientists and their research institutions (Chap 4, "Money"). The extent and nature of scientific competition may vary across contexts, but competition for prizes, priority, and reputation is a common feature of the scientific enterprise (Dasgupta and David, 1994; Stephan, 2010; Cole and Cole, 1973; Cole, 1978).

The third feature of our perspective is that it expects the incentives, benefits, and costs that researchers and research institutions face play a determining role in scientific outcomes. The role of incentives and the determining influence of cost-benefit calculus are central to economics and, not surprisingly, are at the core of approaches to the economics of science. Numerous researchers identify the role of incentive systems in driving scientific behavior, including those that cause deviations from Mertonian ideas noted (e.g., Stephan, 2012; Sauermann and Stephan, 2013; Häussler et al., 2013) above. These factors are also standard features of models of research choices based on knowledge production functions (e.g., Aghion et al., 2008).

The research that we discuss below reflects one or more of these features and the specific forms of these features help shape the implications of that work for thinking about scientific collaborations. Indeed, we could note that a fourth feature that the research we summarize below shares is that each of the articles or ideas suggests at least a partial explanation for scientific collaboration and each shines some light on the fact that research is becoming ever-more collaborative, both in the sense that more projects involve collaboration rather than individual work and in the sense that most collaborations are increasing in size.

II. Views of collaboration and teaming from labor economics

Perspectives in the economics of science regarding collaborative work build on research in labor economics regarding team formation and performance. Although these are not specific to scientific collaboration, they elucidate principles that are applicable to scientific teaming. This literature highlights a fundamental tension between benefits associated with (a) task, skill, or knowledge complementarities and (b) specialization of labor effort against the costs of coordination, which include the costs of communication and the complications of incentive problems, such as free-riding, in team settings.

The models of Becker and Murphy (1992) and Lazear (1998 & 1999) are illustrative. Becker and Murphy model teams as forming because agents become more efficient in a given task when they spend time acquiring task specific skills. Lazear (1998 & 1999) models teams as efficient when, "they make possible gains from complementarities in production among workers, facilitate gains from specialization by allowing each worker to accumulate task-specific human capital, or encourage gains from knowledge transfer of idiosyncratic information that may be valuable to other team members" (quoted from Hamilton, Nickerson, and Owan, 2003, p. 465-466).

This literature balances the potential gains from collaboration against the rising costs of coordination associated with larger team sizes. The interpretation of such coordination costs is broad and includes the specific difficulties associated with communication, goal variance, and the incentive problems associated with teams, including free riding and moral hazard (Alchian and Demsetz, 1972; Holmstrom, 1982). The potential for free-riding in teams plays a particular role in economic models of teaming, although the literature recognizes that, in repeated games, reputational concerns can help limit the deleterious effects of such information problems (Hamilton, Nickerson, and Owan, 2003).

The results of a series of quantitative and qualitative studies on team performance in economics bolster this literature's assumptions regarding the roles of complementarity and coordination costs and paint a richer picture of the associated phenomena (Leibowitz and Tollison, 1980; Ichniowski, Shaw, and Prennushi, 1997; Boning, Ichniowski, and Shaw, 2001; Batt, 2001). The impact of potential knowledge complementarities is also suggested by related research on the economics of teams that finds evidence that team diversity and team size can be correlated with productivity gains (Hamilton, Nickerson, and Owan, 2003). Related research notes the importance of peer effects and social pressures, both within teams and within broader work settings (Mas and Moretti, 2008). Unlike research on the demography of teams in the management literature, this research does not emphasize the role of heterogeneous personal characteristics outside of heterogeneity in tasks, skills, or knowledge (Ancona and Caldwell, 1991; Reagans, et al., 2004).

III. The "burden of knowledge" and its implications for research collaboration

The work of Ben Jones provides an explanation for collaborative science based on the nature of knowledge accumulation (Jones, 2009; Jones, 2010a; Jones, 2010b). In particular, Jones begins with the idea that successive generations of individuals seeking to become experts in a particular domain of knowledge must learn increasing amounts of knowledge to reach the "frontier" as domain-specific knowledge accumulates over time. In Jones's words, "if one wants to stand on the shoulders of giants (taking Newton's famous aphorism), then one must first climb up the giants' backs. As knowledge accumulates, the harder this this climb can become" (p., 104).

Two implications arise directly from Jones's perspective. First, unless the process of learning knowledge experiences dramatic increases in productivity, the burden of knowledge implies that researchers will require longer learning periods before becoming sufficiently expert to make valuable research contributions. Second, the increasing breadth of knowledge relative to the ability of each individual to assimilate it will imply that each researcher is expert in an increasingly small fraction of overall knowledge. Jones describes this effect as the “death of the Renaissance man.” Whereas individuals like Benjamin Franklin could, in the late 1700s, be facile with a substantial fraction of extant knowledge in a variety of fields, it has become difficult in the modern scientific era to be broadly-versed in even a single academic discipline.

These facts suggest an explanation for increasing collaboration: As individuals possess increasingly specific skills and domains of expertise, the cost to reach the knowledge frontier with single-authored projects increases and the potential value of complementarities across individual contributors increases (i.e., since combinations of individuals are increasingly necessary to access knowledge across domains).

While the burden of knowledge explanation of increasing scientific collaboration incorporates ideas about complementarity across knowledge inputs and returns to specialization, it does not rely, as do many others, on institutional factors, the provision of specific incentives, or the costs of specific research investments (e.g., in equipment, materials, etc.). The argument is thus relatively unique in deriving implications for the organization of research principally from an analysis of the implications of knowledge accumulation.

IV. Cost-Benefit Calculus in Scientific Collaborations

Economic analyses of collaborations that do not build directly on the "burden of knowledge" thesis focus more directly on the cost-benefit calculus of researchers when attempting to achieve their career goals (e.g., Katz and Martin, 1997).

Similar to economic models of teaming in other economic areas, these models begin with the idea that the benefits of collaboration arise predominantly from synergies (economics of scope) complementarities among researchers' inputs, which could include complementary skills, research materials, data, or funding, and that the costs of collaboration arise predominantly from coordination costs, which could include the cost of communication as well as the potential loss of academic freedom that is the result of compromise among team members with heterogeneous research interests and aims. Benefits may also arise from economies of scale, principally related to exploiting investments whose purchase, development, or development requires high fixed costs, one extreme example of which is the Large Hadron Collider at CERN. Convinced by the evidence that scientific collaboration provides a range of substantial benefits, a number of funding agencies, and research institutions provide direct incentives for team science that enhance collaboration's innate value.

The costs of collaboration are principally viewed as arising from the difficulty of communication, which increases as the number of collaborators rises and which rises as a function of geographic and intellectual distance. Bikard, Gans, and Murray (2013) also note that increasing collaboration also comes with a reputational cost, not because of the downside risk or error or disgrace, but as a result of the fact that each individual's credit received for discoveries decreases as some function of the number of collaborators. This is a clear implication of the Matthew Effect (Merton, 1968 and 1988), under which junior researcher’s equal contribution to a successful project with a senior colleague will be undervalued as a consequence of the cumulative nature of reputation allocation, and Bikard, Gans, and Murray generalize this implications of the fact that an individual’s project-induced reputational benefit decreases a some function of the number (and nature) of the other individuals on that project.

This cost-benefit approach towards scientific collaboration can, thus, help analyze both the set of projects on which collaboration is sought as well as the set of collaborators on particular projects. The decisions to work with individuals from elite (or non-elite) institutions, with former advisors, with same rank or more-senior or more-junior colleagues, as well as tradeoffs between increasing the probability of research races but sharing credit to a greater extent vs. increasing potential reputation (or financial) gain at the cost of lower odds of research success will, in this view all depend on whether the costs outweigh the benefits of collaborating with particular individuals or groups of individuals.

Gans, and Murray (2013) recognize that a scientist’s choice of whether to collaborate and with whom to collaborate is embedded in a series of other choices, including the choice of project scope (i.e., whether to address a research question involving more or less scientific challenge) which, in turn, have an impact on the scientist’s choice of collaboration and publication strategies.

V. The Benefits of Collaboration

V.1. Complementarity

Economic approaches to team science focus on one general benefit of collaboration: the opportunity to take advantage of complementary sets of skills, tasks, resources, or knowledge bases. One could describe this general set of benefits as either taking advantage of economics of scope (synergies), in which materials or efforts are shared across components of a project or scale (size), in which materials or efforts are most effective when shared across a larger number of researchers, regardless of the domains of each researcher's contribution.

The classical perspective on scientific collaboration contemplates individual, great minds working on complicated puzzles to unlock the mysteries of nature. Relative to this idea, we should expect collaboration to arise when two researchers possess information or approaches which, separately, may not solve the puzzle or would do so with greater time and effort than would result of two or more individuals working towards the same goal were to so in coordination.

Limited work in the economics of science directly examines the specific complementary intellectual inputs provided by individual researchers, although we could envision projects that do so (either survey-based or based on the increasing amount of information scientific journals provide regarding the specific contributions of individual authors). The imputation of such benefits, though, arises both from theoretical perspectives (e.g., Becker and Murphy, 1992; Gans and Murray, 2013) and by appeal to research on creativity and collaboration in other fields. For example, studies in the economics of science acknowledge research demonstrating the value of combining ideas from a diversity of perspectives (Gilfillan, 1935; Hargadon 2003; Porac et al., 2004), through differing social networks (Cummings 2004; Singh 2005; Fleming et al., 2010), and through social interactions (Fleming and Singh, 2010), as well as from empirical work in economics on the benefits of team structures (Hamilton, Nickerson, and Owan, 2003).

One useful point to make here is that the increasing globalization of science, fueled by increased investments in knowledge production in a widening range of countries, particularly in China, greatly expands the set of researchers across which such complementarities could be achieved. This may have an impact on the frequency with which collaboration is selected by researchers, on the specific configurations of collaboration, and on the competition among collaborating teams.

An additional consideration worth noting, on which we will expand in the next sub-section, is that much scientific activity is conducted not by individual researchers, but through laboratories that, in many ways, resemble small firms. Such organizations are designed by their lab directors, who are, typically, also Primary Investigators on large grants, to enable collaborations through complementary skills that take advantage of the opportunity to spread fixed costs across individuals and related projects.

V.2. Economies of scale and scope

One of the most straightforward benefits associated with research collaboration is the opportunity to pool resources and take advantage of shared research materials, data, tools, or equipment. Thus, both the logic of economies of scale (size) and scope (synergies across related activities) play a key role in increasing scientific collaboration.

The phenomenon of *economies of scale* in research is evident in examples such as the Manhattan Project, the Apollo Program, the Human Genome Project, and the Large Hadron Collider at CERN, each of which required the investment of thousands of individuals, hundreds of scientists, and billions of 2011 dollars (Guidice, 2012). In such Big Science project, the benefits of collaboration are obvious: Without the contribution of large numbers of scientists, it would not be possible to exploit the fixed costs of equipment or to address the large intellectual challenges of the project. These principles are also at work in projects of less vast scope, including those that involve equipment, materials, or datasets that support fields or even individual laboratories. In their investigation of the value of Biological Resource Centers, Furman and Stern (2011) find that the inclusion of certified life science materials in central repositories has a positive impact on the rate of growth of knowledge associated with those materials. The effort required to achieve certification, however, involves multiple scientists and high fixed costs; as a result, it yields a benefit that is best used if spread across multiple researchers. This benefit can be realized either in the form of collaborations (i.e,. scientists could withhold certified materials from public collections and request, instead, collaborations with scientists who would like to employ their materials) or materials sharing (i.e., the deposit of such materials in public collections), which could result in increased citations. This highlights that collaboration and citation-receipt are, at times, substitutes and that it is possible for scientists to choose between these two ways of supporting the downstream use of knowledge they generate (Stern and Mukherjee, 2009).

Economies of scale in research are also evident in individual laboratories, in which the fixed costs of equipment, instrumentation, data, and materials are spread across a smaller number of researchers of various experience levels and career trajectories and with common interests. In addition to polish these materials, researchers in a lab pool research funding and the effort associated with securing funding.

The knowledge and skill complementarities we described in the previous section are one type of *economy of scope* that favors collaborative science. Pooling tools, equipment, data, and funding across research project types is another way that collaboration arises from economies of scope in research.

A final example of economies of scope in research is the pooling of risk that may come from working with a number of collaborators on a number of projects simultaneously. As funding agencies, such as the NIH, consider prior research successes a pre-requisites for future funding, increasing the number of one's coauthors enables a researcher to ensure a minimum pool of publications (even shared publications) on which to base one's requests for future financing.

V.3. Attention & Access to Networks to Enhance Impact

A second benefit that can arise from collaboration is that, holding quality constant, increasing the number of collaborators on a research project could enhance the diffusion of ideas associated with that project. In addition to drawing on diverse sets of ideas in order to achieve novel recombinations, a potential benefit of accessing individuals from complementary backgrounds is the opportunity to diffuse information associated with a research project across those heterogeneous groups and their networks. Research in the economics of science has not demonstrated this to be a driver of collaboration or of collaborative impact; however, work on innovation provides evidence consistent with this explanation (Allen, 1978; Tushman and Katz, 1980).

Bikard, Gans, and Murray (2013) note that another way that increasing project team size can lead to enhanced project impact is through the mechanism of legitimacy: This prospect could lead junior researchers to leverage the Matthew Effect to advance their research aims. Bikard and co-authors quote Merton on this issue, who wrote that students may "feel that to have a better known name on the paper will be of help to them" (Merton 1968, p.57; quoted on p. 7 of Bikard, Gans, and Murray). In the context of biomedical science, Azoulay, Graff Zivin, and Wang (2010), find that the unexpected death of a research superstar has a significant and negative impact on the field in which the superstar was active and on the co-authors with whom the superstar collaborated. This result illustrates a problem with the legitimacy-based explanation for co-authoring, which is that it is difficult to separate the boost in research quality associated with a leading-edge contributor relative to the legitimizing or promotional impact of such a contributor to a project. Simcoe and Waguespack (2011) are able to separately identify the impact of research quality from researcher reputation in the context of papers submitted for consideration to the Internet Engineering Task Force, as a result of a random event that resulted in some co-authors' names being excluded from the byline. To be precise, these names were obscured on random occasions in which the author list was revealed as "First author et al." rather than the complete list. Simcoe and Waguespack found that the revelation of the names of prominent authors has a positive, significant and *causal* influence on the research impact of such publications.

V.4. The Potential for Credit Arbitrage

Engers, et al. (1999) and Gans and Murray (2013) point out that, for every individual researcher the decision to collaborate is embedded in a number of other research decisions.

These could include choices about researchers' near- and longer-term scientific agendas, their relative preferences for reputation, leisure, or wealth, their desire to be "helpful" to their fields (Oettl, 2012), and their desire for credit. The desire for credit is complicated by the fact that increasing the number of collaborators on a project can (until diminishing returns sets in) increase both the potential impact of a project and its potential speed. Thus, an individual researcher may join a project (or invite others to join her project) with the intent of enabling that project to come to fruition more rapidly and with greater post-publication impact. This choice involves a tradeoff, though, as the researcher must weigh the value of such rapidity and impact against the cost of sharing credit across a number of co-authors. If it is possible to increase the speed and impact of a project to a greater degree than the cost of decreasing credit; however, adding research project members (or co-authors) can result in a type of "credit arbitrage." The results of Gans and Murray (2013) suggest that this type of arbitrage is possible.

Credit arbitrage provides a specific explanation for an issue of increasing concern to scientists and science policy regarding the use of "honorary authorships," "ghost authorships," or "guest authorships," on papers (Alberts, 2010).

V.5. Institutional incentives & subsidies

A sufficient number of funding organizations, national institutions, and oversight bodies have been convinced of the merits of collaboration for the generation of knowledge and for its diffusion that explicit incentives and subsidies also support increased teaming in science.

In the United States, for example, the National Institutes of Health (NIH) provide substantial support for research collaborations of substantial size. The NIH supports research across universities and other research institutions through "P01" grants, which the NIH describes as "program project grants represent synergistic research programs that are designed to achieve results not attainable by investigators working independently" (NIH, 2013).[3] These projects average $6 million (Stephan, 2012) and cover multiple projects in which the group works collaborative, but with each investigator considered to be independent. Up until June 2010, the NIH's National Institute of General Medical Sciences (NIGMS) operated a program, called "Glue Grants," that provided up to $25 million in direct costs for projects whose research required the involvement of larger sets of collaborators. Further large-scale, collaborative projects supported by the NIH include networked programs , such as the Pharmacogenetics Research Network (Stephan, 2012) and coordinated projects involve substantial collaboration, such as the Human Genome Project (Williams, 2013).

The European Union's Framework Programs for Research and Technological Development, typically referred to as, "Framework Programs," encourage research collaborations across groups and countries. Beginning with the first Framework Program in 1984, the expressed desire to collaborate was identified as a pre-requisite for funding. The Framework Programs have both knowledge *generation* and *diffusion* goals in mind, as some EU funds are reserved for collaborations that involve leading-edge and non-leading edge science countries. Paier and Scherngell (2011) suggest that these programs do, indeed, encourage European research collaborations and Defazio, Lockett, and Wright (2009)

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[3] See, "Program Project Grants (P01)," at http://www.nigms.nih.gov/Research/Mechanisms/ProgramProjectGrants.htm.

provide suggestive evidence that these programs support collaboration and, possibly, research productivity as well.

Incentives in scientific catch-up countries also support collaborative researcher. For example, Ubfal and Maffioli (2011) find that research funding in contributes to increasing rates of collaboration in Argentina. Though through a different mechanism, China‘s decision to provide substantial incentives for publication can also yield an increase in collaboration as China-based researchers attempt to leverage their productive effort and access to data and resources with non-Chinese researchers and with Chinese-origin researchers in the international diaspora.

While there is evidence that the use of partnerships can aid in the response to funding shocks (Furman, Murray, Stern, 2012) and in the effort to seek research funding (Melin, 2000), evidence on the impact of funding for collaboration is more limited. Specifically, while such incentive programs have proliferated in recent years, empirical research has not yet validated the *rate of return* on such projects, particularly not in a way that separates the selection into collaboration from the impact of collaboration on research productivity (although Defazio et al, 2011 do attempt to address this endogeneity). Indeed, such funding may be misguided if there is no particular market failure that funding for targeted collaborative work needs to solve.

VI. Costs

The costs collaboration highlighted by the economics of science include the costs of communication and difficulties that arise as a result of incentive problems associated with team work.

VI.1. Costs & Location

A number of studies have investigated the role of geographic distance in scientific collaborations. However, they do not distinguish the initiation of new collaborations and the deepening of existing collaborations. Katz (Scientometrics 1994) finds that the number of collaborations between pairs of universities in the U.K., Australia, and Canada, decreases exponentially with the distance separating them. Mairesse and Turner (NBER WP 2005) describe the intensity of collaboration between French CNRS condensed matter physicists and how it varies over geographic distance. They find that immediate proximity matters with the intensity of collaboration being an order of magnitude larger within the same site than within the same town.

These descriptive findings conform to other, more influential, studies on the role of geographic distance on interactions between knowledge workers (rather than scientific collaboration specifically). Allen (1970) showed that communications between members of a R&D laboratory decreased exponentially with the walking distance and reached zero after 25 yards. Cowgill, Wolfers and Zitzewitz (2008) analyze the impact of physical distance (and other factors) on interactions between Google employees. They can infer interactions through correlations in bets placed on prediction market. Moreover they have precise data on the seating of Google employees. They find a strong effect of location in the same office, and, to a lesser extent, same floor on interactions between Google employees. However, the effect of proximity vanishes very quickly and being in the same building but a different floor is the same as being in different cities. Furthermore, they are able to use changes in seating arrangements to rule out the possibility that the effect of proximity is due to like-minded individuals being seated together.

A large literature has studied the internet on scientific collaborations, and in particular whether the internet has reduced the importance of geographic distance. Given that this topic is somewhat peripherical to the focus of this literature review, I review it only briefly. A weakness of early studies (see e.g. Gassar and Glaeser, 1998; Rosenblatt and Mobius, 2004; Hammermesh and Oster, 2002) is that they had to rely on time trends. This made it intrinsically difficult to separate the effect from internet from the effect of other changes that may have occurred at the same time such as, for instance, the decline in air travel costs.

Agrawal and Goldfarb (2008) made important improvements to that literature by exploiting plausibly exogeneous variation in the institutional adoption of BITNET, an early version of the internet. Regressing the probability that two electrical engineering departments will have at least one co-publication in a given year on joint Bitnet adoption with pair fixed effects and year fixed effects, they find a large effect for BITNET (+40%). Moreover, they find a stronger effect of Bitnet for pairs consisting of one top tier institution and one middle tier institution and for pairs located at short distances (less than 100km). Results along the same lines are found in Azoulay, Gaule and Stuart (2010) who study the effect of Bitnet collaborations between elite life scientists. BITNET had a positive effect on the initiation of collaboration at short distances, but a negative effect at long distances. Both of these studies on BITNET suggest that lower communication costs may actually strengthen the role of geography in the initiation of new collaborations, rather than diminish it.

In a creative project that exploits the fact that multiple academic departments at the UPMC Paris were relocated over the period 1997-2011 because of an asbestos removal project, Catalini (2013) is able to examine the role of location on collaboration patterns in a precise way that enables the identification of the casual influence of location on collaboration. He finds that random relocations that result in co-location encourage collaborations and encourage breakthrough ideas across academic fields. Boudreau et al. (2012) undertake a similarly creative effort to understand the role of location in collaboration by conducting a field experiment in which they randomize researcher locations finding that those in even briefly collocated environments are more likely to collaborate.

VI.2. Costs, Credit, and Control

Bikard, Gans, and Murray (2013) and Gans and Murray (2013) note that increasing collaboration also comes with a reputational cost, not because of the downside risk or error or disgrace, but as a result of the fact that each individual's credit received for discoveries decreases as some function of the number of collaborators. This insight suggests that changes in the nature of collaboration may reflect changes in the nature of the credit rewards system and the conventions that scientific institutions use to evaluate individual's contributions to the scientific enterprise.

VI.3. Research errors and misconduct

Furman, Jensen, and Murray (2012) and Azoulay et al. (2013) highlight another potential cost that may arise as collaboration increases: The diffusion of responsibility and monitoring that can result in errors in science or retraction. Empirical research has not yet established a link between the number of researchers and the incidence of false science; however, anecdotal accounts of high profiles cases of fraud, including that of Woo Suk Hwang, suggest that geographic distant collaboration played a role in his coauthor's lack of awareness of his unethical activities and research misconduct.

VII. Conclusion & Open Questions

The fact that collaboration in science has become the dominant form of organization is recognized broadly across disciplines interested in studying the scientific enterprise. Within the economics of science, research has begun to address the underlying causes of the trend towards increasing collaboration and to understand its implications. This work has not yet, however, synthesized a view regarding the relative weights of the various factors that contribute to increasing team size and scope.

Another set of central questions on which progress could be usefully made include those related to the rate of return of collaboration. In which circumstances is it optimal for researchers to collaborate? What is the role of competition in driving collaborations and what is its impact on researcher productivity and the advance of science more generally? The central question regarding selection and treatment effects also remains: Does collaboration increase quality or do high quality projects require collaborative efforts? Ascertaining the answer to this question will also help enable better calibration of policy currently directed at supporting research collaborations.

In addition, a number of related questions remain for additional inquiry. These include questions about team formation – i.e., which scientists work with whom? – and about the interrelationship, highlighted by Gans and Murray (2013) regarding collaboration and the choice of scientific agendas.

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