



“A tie is a tie? Gender and network positioning in life science inventor collaboration”

Kjersten Bunker Whittington

Reed College, 3203 SE Woodstock Blvd, Portland, OR 97202, United States

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ABSTRACT

Collaborative relationships are an important anchor of innovative activity, and rates of collaboration in science are on the rise. This research addresses differences in men's and women's collaborative positioning and collaborator characteristics in science, and whether network influences on scientists' future productivity may be contingent on gender. Utilizing co-inventor network relations that span thirty years of global life science patenting across sectors, geographic locations, and technological background, I present trends of men's and women's involvement in patenting and their collaborative characteristics across time. Amidst some network similarities, women are less likely to connect otherwise unconnected inventors (brokerage) and have greater status-asymmetries between themselves and their co-inventors. In multivariate models that include past and future activity, I find that some network benefits are contingent on gender. Men receive greater returns from network positioning for brokerage ties, and when collaborating with men. Women benefit from collaborating with women, and are more likely to collaborate with women, but both men and women collaborate with mostly men. I discuss the implications of these results for innovative growth, as well as for policies that support men's and women's career development.

1. Introduction

Amidst extraordinary strides over past decades, there remain persistent inequities between women and men in a host of outcomes regarding activity in science, technology, engineering, and mathematics (STEM) fields. These include disparities in scientific degree attainment, science labor force participation, salary, the distribution of positions and achievements, material resources and rewards (Long, 2001; Xie and Shauman, 2003; Rosser, 2010). Scholarly and public discussion has highlighted important influences on women's career attainment stemming from the culture and practice of science, the organization and the arrangement of scientific work, and the influence of intersecting social institutions such as marriage and family (National Academy of Sciences, 2006).

Despite focused attention on the topic, less is known about women's collaborative activity, compared to men, specifically regarding their network positioning in research networks and across the science research context (Meng and Shapira, 2010; Meng, 2013; Sugimoto et al., 2015). Scientific collaborations are the backbone of a successful career in science. Research ties facilitate links to additional contacts, assist the diffusion of emergent knowledge streams, and can provide scientists with access to new research opportunities across institutional, disciplinary, and geographic boundaries (Singh and Fleming, 2009; Inoue

and Lui, 2015). Collaboration is also increasingly requisite; rates of collaborative efforts in science are increasing as “lone authorships” are in decline (National Science Board, 2004; Greene, 2007). Amidst an expanding scale of research (as well as significant fiscal constraint), funding institutions are now investing more and more in team science and interdisciplinary initiatives (Bennett et al., 2010; Adams 2012).

A lack of understanding of where women scientists “sit” in networks of collaboration means that little is known about women's embeddedness in the social structure of science, compared to men, as well as how this embeddedness has (or has not) changed over time. Science collaboration is built upon sets of repeated and reciprocal relations between scientists, and linkages between collaborators (and the collaborators of their collaborators) knit together a network of relations (Fleming and Marx, 2006). A scientist's location in this network and the relationships they form and sustain are shaped by the overarching status structure of science, in which hierarchical gender relations prevail (Fox et al., 2017). Against this backdrop is speculation that network benefits may be contingent on gender. By examining gender differences in collaborative positioning, and whether and how network benefits are contingent on gender, it is possible to identify critical factors related to network positioning and women's career attainments in science, and to inform theoretical perspectives about collaborative network mechanisms more generally.

E-mail address: whittington@reed.edu.

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Using the case of patenting collaboration networks in the life sciences, I construct a global patenting collaboration network of ~216 K men and women inventors on ~784 K life science patents across a period of three decades (1976–2005). The collaborative relationships are time-ordered and dynamic, and any given network year represents a portrait of inventors working (individually or together) on commercial research endeavors. Their collaborative relationships define a network of linkages that cross geographic and institutional boundaries through much of the rise and early institutionalization of the biotechnology industry.

The novelty of this data, and the information it provides, comes from the incorporation of two increasingly prevalent, yet not previously combined, strategies to ascertain information about scientific collaboration in a network context. The first regards the challenge of disambiguating patenting and publishing records. Until very recently, data was not readily available to link inventors and authors to their patenting and publishing records in a way that would allow researchers to easily construct unique collaborative profiles for scientists over time. Although not hindering research completely (see, for example, [Fleming and Marx, 2006](#); [Lai et al., 2010](#); [Lai et al., 2011](#); [Inoue and Liu, 2015](#)), this has slowed the proliferation of knowledge about collaborative networking in science. In this research, I follow efforts of previous work to disambiguate inventor records and construct networks of collaboration over time ([Lai et al., 2010](#); [Lai et al., 2011](#)). Similar efforts can be found in the United States Patent and Trademark Office (USPTO) PatentsView platform, which employs probabilistic methodologies to disambiguate inventor records in a relational database ([USPTO, 2016](#)).

The second challenge relates to the omission of gender identity¹ in patenting and publishing records ([Frietsch et al., 2009](#)). While information on women's patenting and publishing activities can be gathered by self-report on surveys, or through hand-coded case studies, the lack of information at the record level complicates research on men's and women's network positioning, because details about science collaborators (and the collaborators of their collaborators, etc.) need also be known. In this work, I utilize name frequency databases to create a probabilistic likelihood of inventors being male or female, a strategy in line with others ([Moody, 2004](#); [Frietsch et al., 2009](#); [Meng, 2013](#); [Sugimoto et al., 2015](#); [Larivière et al., 2013](#)). Although an imperfect method, such data would be challenging to procure otherwise; indeed, organizations with substantial resources otherwise have, and continue to, rely on similar methodology ([Elsevier, 2016, 2017](#)).

To this researcher's knowledge, this work represents the first effort to employ both strategies in a relational fashion to address questions about women's collaborative positioning, compared to men, using network methodology in a global network context over time.² I use this network to present descriptive statistics on inventors patenting rates and collaborative profiles, over time, as well as to report on a wide variety of network measures commonly considered to be relevant to innovative output. I then leverage the longitudinal nature of the data, and its relational components, to investigate the possible moderating influence of gender on network benefits to scientists' future commercial activity, finding evidence of some network contingencies for men and women inventors.

2. The case: patenting in the life sciences

My focus on patenting – as opposed to other collaborative endeavors in science – is guided by both methodological and substantive factors.

¹ The terms “sex” and “gender” commonly refer to the biological versus social construction of men and women. In this analysis, I use “gender” to refer to both physical and social difference, and use the terms “men and women” and “male and female” interchangeably.

² See [Frietsch et al. \(2009\)](#) and [Meng \(2013\)](#) for comparable work outside of a network context. Outside of gender, see work by [Fleming and colleagues \(Fleming and Marx, 2006; Fleming et al., 2007\)](#) and [Inoue and Liu \(2015\)](#).

While publishing has long been regarded as the “coin of the realm” for academic science ([Storer, 1973](#)), this sector has witnessed a sea change in recent decades with an explosive increase in patenting, licensing, start-up incubation, and founding of companies, most notably in the life sciences ([Henderson et al., 1998](#); [Mowery et al., 2001](#); [Owen-Smith, 2003](#); [Owen-Smith and Powell, 2003](#)). At the same time, scholars have recently turned an analytical lens beyond publication to additional indicators of research productivity, including those related to academic and industrial entrepreneurship and commercial activity. Innovation is connected to increased publication productivity ([Stephan et al., 2007](#); [Azoulay et al., 2009](#)), and is valuable for academic success and rewards more broadly ([Jacobs and Frickel, 2009](#)). In addition, a focus on patenting allows for attention to be paid to the relationship of institutional location and gender equity in science, as the commercial context involves activity beyond academia in industry science, non-profit research institutes, government agencies, and pharmaceutical firms and chemical companies. Cross-sector activity knits together the social structure of science and presents a more accurate portrayal of science collaborations in the biomedical sciences. Methodologically, patenting data is publicly available, and is widely used in social and economic circles to assess individual, state, regional, and national indicators of innovative activity. A base of knowledge exists about inventor network relationships in the science realm ([Fleming et al., 2007](#); [Balconi et al., 2004](#); [Obstfeld, 2005](#); [Inoue and Liu, 2015](#)), allowing for useful comparisons and meaningful implications.

While patenting and publishing activities are distinct – patents grant exclusive rights, and must meet criteria of being useful, novel, and non-obvious – there are similarities. Both tend to be conducted by teams of scientists utilizing recognized research practices, who formulate claims based on extant literature. Both codify results and mobilize evidence, and are governed by an external evaluation system. Furthermore, scientists with academic ties often publish and patent the results of the same research activities in patent/publication pairs ([Murray, 2002](#); [Murray and Stern, 2007](#)). That said, commercial activity is more likely to be taken on by those who are highly productive in other performance metrics, such as publishing ([Stuart and Ding, 2006](#)), and to occur in certain settings over others (such as industrial science, and in research universities). The concern regarding women's involvement is that the increased emphasis on commercial activity may heighten gender gaps in status because those who are already successful appear better able to capitalize on commercial success ([Colyvas et al., 2012](#)).

As with publishing, a considerable body of research has found that women receive fewer patents than men, and patent at lower rates, with some decrease in the gender disparity over time ([Naldi et al., 2005](#); [Thursby and Thursby, 2005](#); [Ding et al., 2006](#); [Stephan and El-Ganainy, 2007](#); [Kugele, 2010](#); [Colyvas et al., 2012](#); [Sugimoto et al., 2015](#)). Some industry settings – particularly firms of a “network form” ([Powell, 1990](#))—reveal more equity than others ([Whittington and Smith-Doerr, 2005, 2008](#)). Compared to men, women are also less likely to be present in other commercial endeavors, such as licensing ([Duque et al., 2005](#)), consulting ([Corley and Gaughan, 2010](#)), participation in private sector scientific advisory boards ([Ding et al., 2013](#)), and company founding ([Lowe and Gonzalez Brambilla, 2007](#)). Research finds that a significant hurdle for women may occur at the stage of *first* involvement, especially in the academy where such activities are not “required” ([Whittington, 2011](#)). In interviews with women scientists at a prominent university, [Murray and Graham \(2007\)](#) report that women describe less exposure to the commercial process and fewer opportunities to disclose than men (see also [Ding et al., 2006](#)). Women also report fewer invitations from others to participate in commercial activity, and different sources of support for commercial involvement than men—women from close colleagues in comparable positions (and from technology licensing offices), and men from senior advisors.

Women patent less than men, however it remains unknown how they are integrated in the broader collaborative community. Given the importance of network factors in innovative activity more generally, it

is reasonable to assume that accounting for these may help explain gender disparities in innovation, or reveal sites for which targeted policy or best practices may be applied. The data used in this analysis speak to women's positioning in co-inventing networks *at the point of their first patent and beyond*. If the hurdle of first patenting is the point of greatest disparity between men and women, we might anticipate similar collaborative locations between men and women scientists who have already reached this milestone. However, the fact of divergence in sources of support and connection to the commercial process for men and women (and a long line of research on the ways in which gender infuses the organization and practice of science (National Science Board, 2004)) implies that gender may interact with opportunity in ways that reveal differential locations for men and women in commercially collaborative networks (and perhaps differential benefits of collaborative ties down the line).

3. Collaboration and networks

The network literature is clear that technical knowledge diffuses through social networks of relations (Breschi and Lissoni, 2004; Singh, 2005; Walsh and Maloney, 2007; Singh and Fleming, 2010). With some important caveats related to the characteristics of one's collaborators as well as the nature of the tie (see Perry-Smith and Shalley 2003; Fleming et al., 2007; Rost, 2011), those with more collaborators have been found to publish more articles, in higher impact journals, and accrue more citations (in a faster amount of time) (Lee and Bozeman, 2005). Some research finds women less likely to collaborate than men (Scott, 1990; Kyvik and Teigen, 1996; Hunter and Leahey, 2008), although others find no difference or that women collaborate more (Prpic, 2002; Gaughan and Bozeman, 2002; Bozeman and Corley, 2004; Bozeman and Gaughan, 2011). In some settings women are less likely to collaborate internationally (Uhly et al., 2015), which can carry implications for downstream citation impact (Elsevier, 2016), as can cross-sector collaboration.

A broader literature suggests that women and men tend to foster qualitatively different patterns of interaction within their work settings (Kanter, 1977; Ibarra, 1992; Smith-Lovin and McPherson, 1993), with implications for women's performance. Men tend to have predominantly male networks, while women tend to have female or mixed networks (McKinsey and LeanIn.Org, 2015). Women tend to have network compositions with more strong, dense, relations (as opposed to diverse or spanning “brokerage” ties³), and tend to be tied to fewer influential individuals (Brass, 1985; Moore, 1990; Ibarra, 1993; McGuire, 2002). In some settings, these different types of connections have been shown to provide alternate routes to success for men and women (Ibarra, 1997). Some of the variation is likely related to structural differences in occupation and/or job rank (Brass, 1985; Moore, 1990; Ibarra, 1992), yet beliefs about gender also form a background frame from which workplace decisions and outcomes are made (Ridgeway, 2011), and especially in the context of science and entrepreneurship (Wajcman, 1991; Thébaud, 2010; Tinkler et al., 2015). Women are also often excluded from resourceful networks despite their career location (Miller et al., 1981; Ibarra, 1992).

If network influences on collaborative relations mimic that of other types of work relations, we might expect to see qualitatively different positioning and collaborative profiles between men and women: women may be more likely to be tied to other women or to be in mixed-sex inventor teams (*homophily*), may have fewer spanning ties to unconnected others (*brokerage*), and fewer may be involved in *cross-sector* inventing. We might also expect to find decreases in these differences as the number of women in the patenting network grows over time (in

tandem with the growth of women in biomedical fields more broadly, and reductions in gender disparities in STEM more broadly); thus, accounting for time in the network may reduce the extent of women's lower aggregate patenting activity compared to men. But this work allows for an examination of areas where previous literature is quiet: the extent to which women are *isolated* or on the *periphery* in collaborative science spaces, whether gender differentials exist between men and women when considering frequently invoked centrality measures (*degree centrality*, *closeness centrality*, *aggregate constraint*, etc.⁴), and how they may differ in the types of collaborators they have (*collaborator status and positioning*).

3.1. Gender and rewards for social capital

In addition, a scant literature suggests that gendered practices in the workplace may also lead to gender differences in the ways in which rewards for social capital are realized or received (Brass, 1985; Ibarra, 1997). For example, there appears to be a greater ability among men to leverage their positions and credentials (e.g. hierarchical rank, existing network contacts, educational degrees) into centralized network positions (Miller et al., 1981; Ibarra, 1992). In a case study of promotion in a workplace, Burt (1998) finds that female managers most likely to be promoted have strong ties to superiors and dense networks of close ties to colleagues, whereas successful men receive more from maintaining important brokerage, or spanning, ties (of which women had fewer) (Burt, 1992, 2005). Burt attributes this to the need for women to attain “borrowed social capital” in the eyes of their superiors, who make decisions about their upward mobility (1998, page 6). Related work utilizing an experimental setting in venture capital decision-making also finds tie contingencies based on gender (Tinkler et al., 2015). In a simulated environment where differences between a male and female entrepreneur seeking funding were otherwise equal, Tinkler and colleagues found that although both men and women entrepreneurs benefited with the “endorsement” of a trusted colleague, the tie benefits women received were much greater and consequential than they were for men. Like Burt, Tinkler et al. highlight the status and/or signaling effects that ties can provide, and suggest that women more so than men benefit from certain indicators of potential. Connections to key players – and also technical background in their context—helped to instill confidence in evaluators and mitigate uncertainty in their abilities in this male-typed setting. In both cases, underlying status processes yield network influences that differ or are altered for men relative to women. On the one hand, Burt's (1998) work suggests that the type of influential tie may vary: women in the business setting he studied did not see as much reward for spanning relations (e.g. connections to diverse, otherwise unconnected, others) as did men. On the other hand, the work of Tinkler et al. finds that while network signaling is helpful for both men and women, it is particularly consequential for women.

3.2. Analytical approach

The collaborative space is the coin of the realm of working scientists, and previous work clearly identifies networks of relations to be critical for the production of scientific work. Gendered expectations infuse social interaction in science, and this domain is particularly masculine-typified (Faulkner, 2000). For this there is reason to expect that network factors are important in understanding gender differentials in patenting, and this has yet to be comprehensively examined. We do not know the extent to which women and men foster relationships with different types of collaborators in science settings, and/or receive differential benefit from these ties. Furthermore, “complete” network data is rarely in hand – that is, information that includes all

³ Discussed in more detail in later sections, brokerage is a network construct that refers to individuals with ties to others that have no other available connection between themselves (Burt, 1992).

⁴ Table 1, discussed in more detail in Section 5, presents definitions of these and other network constructs utilized in this work.

direct and indirect ties, and activity that takes into account typical scientific collaborative relations across sectors, regions, and institutional locations. In this analysis I investigate whether or not there are gender differences in rewards for inventor positioning, as well as for the characteristics and connectedness of their collaborators. While this work does not attempt to adjudicate between the many potential underlying mechanisms responsible for these contingencies, clarification of critical factors related to network differentials can inform theoretical perspectives and provide a roadmap for targeted inquiries in future research and policy development.

The principle aims of this work are thus to:

- 1) characterize men's and women's patenting and commercial network activity, as well as that of their collaborators;
- 2) describe men's and women's network positioning over time across a variety of measures commonly mobilized in network analyses of innovative outcomes;
- 3) ascertain the extent to which there are moderating influences of gender on network and collaborator characteristics as they relate to scientists' future commercial activity, other things equal.

4. Data

To construct co-inventor relationships over time, I collect patent records from an institutional sample of dedicated biotechnology firms and their partner organizations (universities, non-profit research institutions and hospitals, pharmaceutical firms, health and chemical corporations, and government agencies) active in the biotechnology industry during the time period 1976–2008. Dedicated biotechnology firms (DBF) in this sample are defined as any organization with a human therapeutic and diagnostic focus, excluding firms that focus on agriculturally-based technology or other non-human agendas. The firm sample is curated from a widely accepted industry database, *Bioscan*. As described in detail elsewhere (Powell et al., 2005), this industry database catalogs nearly the entire population of biotechnology firms, and lists all partner organizations with which firms maintain contractual relations during this time period. I include all patents assigned to DBF firms during the time period, as well as the patents of all global partner organizations contractually related to the DBF firms during the same time period. I also include the patents of all 89 research-intensive U.S. universities during this time period designated as “Research 1” via the [Carnegie Classification of Institutions of Higher Education \(n.d.\)](#).⁵ The full institutional sample thus consists of the stock of patents assigned to 1524 firms and institutions: 568 public and private DBFs, 220 public research organizations and research hospitals, 245 pharmaceutical and other chemical and health-related multi-national corporations, 35 government agencies, 103 universities, and 120 biomedical companies. All firm patent records are then resolved to the inventor level.

Alongside others (Lai et al., 2010, 2011), I consider inventions to be from the same person when two inventors match in first, middle, and last name (or part thereof, in the case of missing middle or first names). As described in additional detail in Whittington (2007, 2009), I incorporate an algorithm that allows for matches when similar first, middle and last names and one other matching characteristic – a similar city and state, assignee name, and/or the same primary and secondary technology class—are present.⁶ The resolved inventor list was then matched to a second database of inventors, this time containing the

total corpus of USPTO patenting records during that time frame (i.e. including patents beyond the life sciences) (Lai et al., 2010). This allowed for inventor records in the sample to include patents granted to organizations outside the purview of the initial firm and institutional sample. All dates utilized in the analysis stem from the date the patent application was filed with the USPTO. I focus on the years 1979–2005 in the analysis to accommodate the typical waiting period of 2.5 years between filing and grant date of the patent. This allows for the inclusion of patents filed in 2005 that may be granted up to 3 years later.

Multi-national corporations, universities, governments, and other institutions patent across a variety of disciplines and topics (for example, consider the range of patents granted to large conglomerates such as Mitsubishi Group, or to universities, both of which are in the sample). I take steps to provide an appropriate field boundary to the network so as not to calculate network influences based on connections to industries very far-afield. I designate “core” biotechnology classes to be those that comprise the 90th percentile and below of the patents assigned to DBF firms. I include all scientists that *always* patent in the core (i.e. scientists for whom *all* of their patents in their portfolio fall within these classes), scientists that *sometimes* do (i.e. scientists for whom at least one of the patents is a core patent), and all scientists from the patents of DBF firms. I also include all *never* inventors (i.e. scientists who never patent within the core patenting classes) that are within two steps of an *always* or *sometimes* inventor. I include “*nevers*” in the network calculations to avoid truncating interdisciplinary ties that may serve an important network function, but I remove these individuals from the descriptive and statistical analyses, focusing only on scientists for whom always or at least sometimes patent within core biotechnology patenting classes.

I code inventor gender with the assistance of lists of first names provided by the 1990 US Census and other international organizations. The U.S. Census list provides names that comprise the 90th percentile and below of the set of baby names registered with the U. S. Social Security Administration, classified by sex of the baby and with cumulative percent. A name found only on one list is assigned to the related gender. In the case of “androgynous” names, where a name appears on both lists (< 10% of names), the cumulative percentage for the name for each sex is compared, and gender is assigned to the least-rare case.⁷ I supplement with additional name lists that focus on common names in other countries, when available.⁸ Roughly 25% of the sample has a first or middle name that cannot be identified. Much of the missing data for inventor gender occurs for foreign names, and those of Indian and Asian descent are particularly difficult to code for gender using these approaches. I do not remove these individuals from network calculations to maintain the connective integrity, but exclude them from comparisons of men and women inventors in the statistical models.⁹

The two-step network contains 783,835 patents to 215,450 inventors across the approximately thirty-year time frame. There are 114,483 inventors patenting in biotechnology core classes and/or in biotechnology firms (always, or at least some of their time, in the network). Of these, 82,579 inventors have “gender-resolvable” names and do not have missing data on other measures. Unless otherwise noted, all statistics are based on this final sample count.

⁷ If both are “rare” or both are “common” (close in percentile), the decision is not automated and the record is hand-coded using available references located for the inventor in question. I use a variety of supplementary sources for hand-coding, including online CVs, biographies, website information, and/or US government documents. Less than 1.5% of the inventors had androgynous names for which sex was unable to be determined.

⁸ There are no substantively different model results when I conduct the analyses using a continuous variable based on the cumulative percent (i.e. “probability of being female”) for the subset of matched US names.

⁹ This challenge and the magnitude of the missing data is not unique to this dataset. See similar discussions and treatment in Elsevier (2016, 2017) and Larivière et al. (2013). Models that include a third category for “gender unknown” do not change the substantive conclusions of this research.

⁵ The firm-level approach avoids the challenge of developing a set of technology classes or key words to define the sample, which can change over time and restrict the presence of interdisciplinary ties.

⁶ A flagging system provided an indication of records in need of hand-coding when potential errors may occur, and sensitivity checks on these and a random sample of 5% of the data were conducted. In addition, a suite of sensitivity analyses were performed to interrogate sample integrity, such as exclusion criteria and network diagnostics. Additional details are available from the author upon request.

Table 1
Network Measures and Definitions.

Location in the network	
Size of Network Component	Defined as the number of individuals in the component containing the inventor who can reach each other through direct or indirect ties.
Membership in the Main Component	The main component is the <i>largest, completely connected</i> sub-component of a network. All inventors in the main component can reach each other through direct and/or indirect ties.
Centrality and Reachability	
Network Isolate	Inventors who have no collaborators/co-inventors. Also referred to as collaborative isolates and sole inventors.
Degree centrality	The number of co-inventors an inventor has in a given year (i.e. direct ties)
Closeness Centrality	Measures reachability in terms of the relational “distance” (as measured by the sum of direct or indirect steps) from the inventor to others in the network. Defined as the number of inventors in the network divided by the sum of all distances between the inventor and each other inventor (Sabidussi, 1966).
Strategic Positioning and Control	
Betweenness Centrality	Measures the extent to which the inventor sits on paths that link to other inventors. Defined as the proportion of all “shortest paths” between pairs of inventors that include the inventor (Freeman, 1977)
Clustering coefficient	Measures how close an inventor’s co-inventors are to a complete graph (where all are connected to each other). Defined as the proportion of links between co-inventors divided by the number of links that could possibly exist between them. (Watts and Strogatz, 1998)
Broker/brokerage role	Defined as an inventor who is connected to other inventors that have no direct connection between themselves (Burt, 1992).
Aggregate constraint	A measure of the importance, or exclusivity, of an inventor’s ties, given the tie distribution of their co-inventors. Defined as the sum of the dyadic constraints between an inventor and each of their co-inventors, where dyadic constraint is the proportional strength of each tie given the co-inventor’s ties to others. This measure captures the extent to which an inventor has relations with co-inventors that are also strongly connected to each other. The higher the constraint, the less the inventor is in an exclusive (or control) position relative to their co-inventors (de Nooy et al., 2011)
Type of ties	
Homophily	The extent to which an inventor is tied to other inventors that have a similar characteristic, such as gender, race, age, class, or any other distinguishing trait. Defined in this work as the percentage of co-inventors who are identified female (McPherson et al., 2001).

5. The commercial life science network

Table 1 presents definitions of key network constructs utilized in the analysis. I construct the network¹⁰ such that ties are formed three years prior to the application date of a patent and remain in effect until three years after, although the substantive results of the network analysis remain unchanged if a 2-year collaboration period is utilized instead.¹¹ Ties are valued by the number of patents in which inventors are jointly listed in a given network year.

Network visualizations of this size are often crowded by nodes, ties, and overlapping network components. Fig. 1 provides a portrait of the collaborative structure through a focus on the largest connected network component (sometimes referred to as the “main component”) of the life science commercial network across all years (containing 92% of the inventor sample). In the main component every scientist could— theoretically – reach everyone else through direct or indirect ties. While inventors are not likely to have practical access to all members of a main component in any year, the concept is none-the-less a useful one for to provide traction on differences between inventors who are working “where most of the action is” in the biotechnology collaborative space, and those who collaborate more afield.

Each node in Fig. 1 represents a commercial scientist, colored magenta, blue or yellow for women, men, or “gender unknown”, respectively. Aside from the large cluster of yellow “gender unknown” inventors in the top right hand corner (the bulk of which are affiliated with patents assigned to Asia-based firms), a simple visual inspection of Fig. 1 suggests that women are more or less evenly distributed throughout the network – that is, they are not all clustered to the periphery or elsewhere, a point given further attention later. Within any given year, the main component of the yearly network is smaller, and contains fewer inventors (yearly networks include between 40 and 80%

of inventors), because these years reflect active collaborations rather than a cumulative total across time.¹²

6. Patenting activity and characteristics of collaborators

6.1. Patenting activity

In the aggregate, women comprise 24% of the biotechnology inventor population across years and organizational settings, and are assigned 38% fewer patents than men (Table 2).¹³ On average, women hold 5.4 patents compared to men’s average of 8.4. Patent counts are heavily skewed, however, and many inventors have only one or a few patents while only a handful have many. In this, gender disparities are upheld. Men hold a median of 4 patents and women a median of 2, and women are also more likely to be “one-time” inventors than men (32% of women versus 21% of men). Furthermore, they are overrepresented at the lower counts – women represent 26% of inventors with 1–5 patents, but only 19% of those with 5–10, 15% with 11–25, and 13% at higher counts. Women also have a higher number of years for which they exhibit no collaborative activity after they enter the network (0.56 versus 0.27 years, respectively).

The average year of first patent in the sample for women is three years behind that of men (1991 versus 1988, respectively), but the data reveal the extraordinary growth of women’s involvement in patenting over time. This can be seen both in the percentage of women inventors applying for patents, and in the percentage of patents with at least one woman inventor (Fig. 2a and b), and the percentage of women in the pool of “new entrants” to patenting is also growing each year (Fig. 2c).¹⁴ Given these trends, it is important to note that differences

¹⁰ The data for this analysis represent two-mode affiliation data, where the inventors are the actors and each patent is the event. The affiliation network, when multiplied with its transpose, produces a one-mode actor by actor network. In this way, a connection between actors is assumed strictly by their collaborative activity. In the network, scientists are connected to those they patent with, are indirectly connected to those their co-authors patent with, and so on.

¹¹ If inventors patent again together outside of that window, their connection is maintained throughout the length of their collaborative history together.

¹² As few as 40% of inventors are in the main component in the early years of industry development (1976–1982), whereas there are ~80% in the main component in the network’s most integrated years (1997–2000).

¹³ Unless otherwise noted, all reported differences are statistically significant at the $p < 0.001$ level (two-tailed).

¹⁴ The “fall-off” in numbers near the end of the sample is a common artifact of patenting data, for which there is a lag between application date and grant date. If we were to follow the sample out several more years, we would expect to see rising numbers for both men and women in the later years in the dataset.

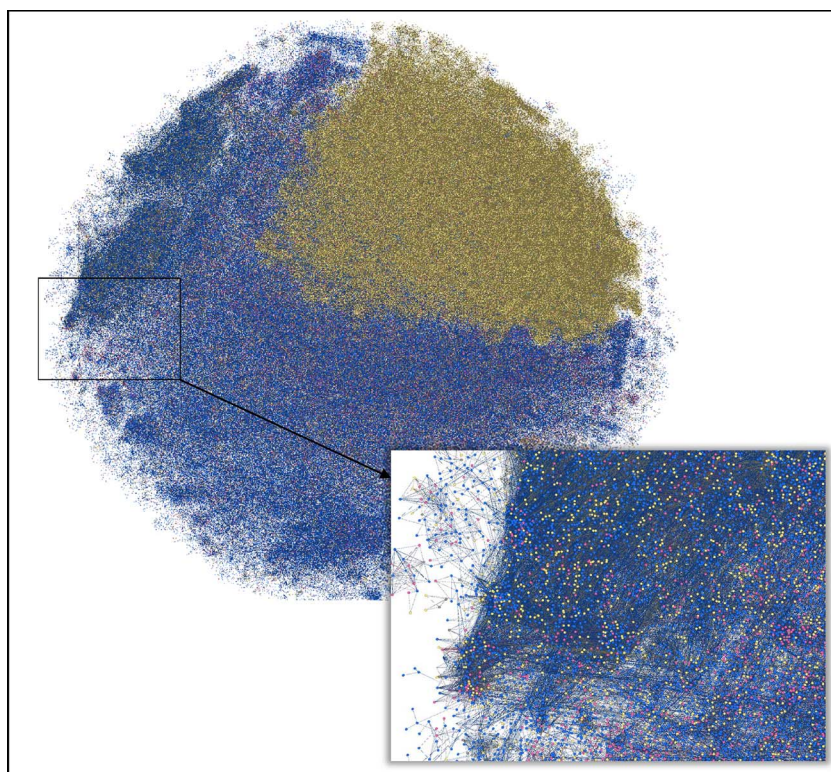


Fig. 1. Largest main component of inventor collaborations in the global life science community, by inventor gender (1976–2005). Global network across all years, with the following node color specifications: women (magenta); men (blue); “unknown gender” (yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Patenting activity and inventor characteristics, by gender.

	Men Inventors	Women Inventors	Percent Women
Patenting activity by organizational affiliation	(% of Men)	(% of women)	(% of total)
Dedicated biotechnology firms	9.15	12.27	29.92
University	15.88	16.41	24.76
Pharmaceutical firm	18.56	20.19	25.71
Chemical and health corporation	27.99	23.51	21.09
Nonprofit research hosp./institute	6.95	8.79	28.70
Government	2.41	3.03	28.57
Other biomedical/biotech company	3.64	3.27	22.26
Multiple forms (patents include multiple org forms)	1.17	1.90	33.96
“Form switcher” (patent profile spans forms)	14.23	10.64	19.22
Total	100	100	24.15
Total patent count			
Mean	8.43 (17.07)	5.36 (10.62)	
Median	4	2	
Total patent count, normalized (years since first patent)	0.60 (1.21)	0.51 (0.98)	
Percent of US-based patents in portfolio	0.68	0.63	
Core life science inventor, always ^a	0.51	0.68	30.0
Year of first patent	1988 (7.35)	1991 (6.11)	

^a Reference category for “always” is “sometimes” a core life science inventor N = 82,579.

seen in aggregate statistics may be related to women’s later entrance to the commercial realm than men. For example, gender differences in total patent count decrease when accounting for years since first patent: men patent approximately 0.60 patents/year versus women’s average of 0.51/year (Table 2). This corresponds to a reduced difference in yearly output (down to 16%) considering differentials in the number of years since first patent.

Most inventions are assigned to institutions (as opposed to individuals), and the bulk to only one organization at a time (97%). Across organizational settings, fewer women inventors in the sample are in multi-national health and chemical corporations and other

biomedical companies (less than 25%) than in other settings,¹⁵ however the biggest difference is between men and women with inventing activity that crosses sectors or institutional forms. Women make up only 19% of those who are “form-switchers” (that is, inventors with a patent portfolio that spans organizational forms). Interestingly, they make up a higher proportion of inventors with cross-sector activity (i.e. inventors

¹⁵ These proportions complement data collected from the Survey of Doctorate Recipients during this time period, where the patenting population is 18% female in the life science university setting and 21% female in the life science industry setting (National Science Foundation, 2002). In this sample, women inventors comprise 19% of those who have *always* as well as *ever* had university assigned patents, and 23% of those with industrial classifications.

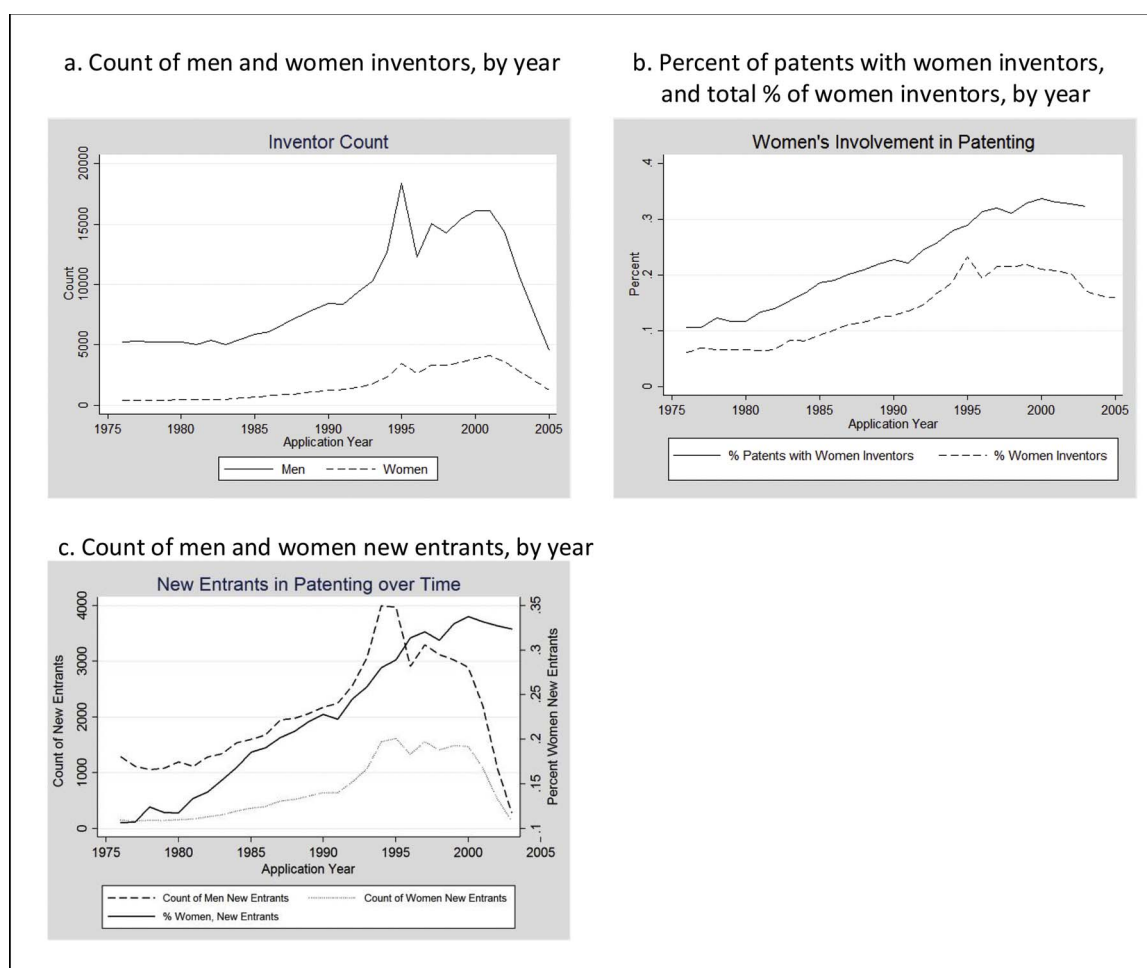


Fig. 2. Longitudinal Trends in Prevalence, Involvement, and Entrance to Patenting (N = 82,579).

on “multiple forms” patents, or patents that are assigned to more than one organizational form) than any single institutional location (33%), although only a very small percentage of scientists in the sample engage in this kind of work.

Women inventors in biotechnology are not collaborative isolates (Table 3). They reside on larger inventor teams than men (women have an average of 4.1 inventors on their patents and men have 3.6 (a 14% increase)), are less likely than men to be sole inventors (15% of women are singleton inventors versus 20% of men), and are less likely to be on a team with just one other person compared to men (19% versus 22% of women and men are in teams of two). Although women have fewer *total* collaborators than men (6.94 compared to 8.63), they have more than men when the measure is normalized to total patent count (1.69 for men compared to 2.15 for women).

6.2. Collaborator profiles

There is a general trend towards gender homophily in the inventing network, despite the small percentage of women in the sample (Table 3). Whereas twenty-eight percent of women’s collaborators are women, only 18% of men’s collaborators are. The relative difference between men and women is highest among those that work in pharmaceutical firms (a 47% percent difference) and multinational chemical and health corporations (70%), and hovers around 20–25% for those in dedicated biotechnology firms, universities, non-profit research hospitals, and universities. The organizational variation appears to be related to differences across settings in *men’s* proportions of women collaborators; women’s proportions remain relatively similar regardless of setting. The general trend of homophily underscores the persistent role

of status and similarity in network formation (McPherson et al., 2001), and provides implications for the role that diversity may play in the scientific workforce. On one hand, although the content and science may be the same, women inventors are involved in networks of collaborations that are—at least as related to gender—significantly more diverse in nature across settings. The implication is that women may “bring into and/or better locate other women” in the commercial context. On the other hand, the fact that there are far fewer women than men in life science commercial networks, suggests that the tendency for homophily may mean women experience a reduced set of available collaborators compared to their male colleagues.

Women and men have collaborators that are similar in other respects. Their collaborators are similar in the numbers of organizations to which they are affiliated, their international orientation, their time spent in the network, prior patenting experience and total patent counts. However, as Table 3 reveals, while both men and women have collaborators that are, on average, more experienced and commercially productive than them, women’s relative difference is greater than men’s. For example, while men’s collaborators have spent 32% more time in the network than they have, women’s collaborators have spent roughly 50% more. Men’s and women’s collaborators are more prolific inventors than they are (on average), but men’s collaborators are more similar to them in their total number of patents than are women’s collaborators. These asymmetries may be related to myriad factors that deserve further treatment, including the types of collaborative relationships men versus women inventors foster, the availability of collaborators given inventors’ positions in the network, and the types of projects or roles men and women embody in their organizations, among other factors.

Table 3
Inventor collaborative profiles, by gender.

	Men	Women
Size of inventing team (average)	3.60 (2.78)	4.12 (3.22)
% sole inventors, ever	19.51	15.46
% dual Inventor (team of two, ever)	22.05	18.88
Total number of collaborators	8.63 (10.99)	6.94 (7.97)
Total number of collaborators, normalized by total patent count	1.69 (1.58)	2.15 (1.92)
N = 82,579 (all inventors)		
Collaborator Gender By Inventor Organizational Affiliation (%F, inventor's collaborators)		
Dedicated biotechnology firms	0.22 (0.25)	0.27 (0.27)
University	0.19 (0.27)	0.25 (0.31)
Pharmaceutical firm	0.18 (0.23)	0.29 (0.30)
Chemical and health corporation	0.14 (0.21)	0.29 (0.32)
Nonprofit research hosp./institute	0.22 (0.22)	0.28 (0.32)
Government	0.22 (0.27)	0.32 (0.31)
Other biomedical/biotech company	0.14 (0.22)	0.34 (0.37)
Multiple forms (only span forms, patent-level)	0.23 (0.26)	0.30 (0.29)
"Form switcher" (spans forms across profile)	0.20 (0.18)	0.29 (0.22)
Total	0.18 (0.23)	0.28 (0.30)
Collaborator profile (avg. across inventor's collaborators)		
Number of unique organizational affiliations	1.52 (0.67)	1.57 (0.73)
International Orientation (1 = all collaborators US based)	0.68 (0.43)	0.63 (0.45)
Years in network	14.82 (4.62)	14.49 (4.57)
Total patent count	12.82 (14.10)	12.40 (14.37)
Degree Centrality	6.56 (4.96)	7.06 (5.10)
Brokerage Positioning (1 = all collaborators are brokers)	0.68 (0.32)	0.67 (0.32)
Always located in the Network Main Component (1 = all collaborators are located in main component)	0.26 (0.32)	0.26 (0.33)
Collaborator asymmetry (% diff, inventor from collaborators)		
Experience in network (years)	31.63 (0.72)	49.56 (0.68)
Total patent count	287.65 (7.60)	407.64 (8.93)
Number of unique organizational affiliations	25.43 (0.58)	34.49 (0.63)
N = 78,066 (all inventors with collaborators)		

7. Network positioning

Network scholars utilize a number of measures that capture the extent to which women and men are reachable or more centrally connected to others in the network, and I evaluate men's and women's locations across a set of commonly used and robust measures incorporated in literature elsewhere (Table 1). The measures cluster into three broad sets of categories: 1) inventor location in the network; 2) inventor "closeness" to other inventors, including immediate collaborators and those more than one step away (centrality and reach); and 3) the degree to which an inventor is strategically placed, on short paths to highly central others ("betweenness") as well as to "non-redundant" others ("brokerage").

It is not the case that women are more likely to be isolated inventors or clustered in network components of small size (Table 4). A similar percentage of men and women are located in the main component of at least one network year (78% versus 75%), and women are more likely than men to reside in the main component *every* year (35% versus 25%, respectively).¹⁶ Subsequent analysis (not shown in the table), finds these trends hold across time, with little deviation through the network years.

Table 4 and Fig. 3a reveal little difference between men and women in degree centrality, measured by the number of ties that are one path length away. This captures the number of active collaborations, across

Table 4
Inventor network location (across patenting profiles), by gender.

	Men Inventors	Women Inventors
Location in yearly network main component (at least one year)	0.76 (0.43)	0.78 (0.41)
Location in yearly network main component (all years)	0.25 (0.44)	0.35 (0.48)
Degree centrality	4.78 (5.11)	4.76 (4.56)
Closeness centrality	0.04 (0.03)	0.04 (0.03)
Clustering coefficient	0.56 (0.36)	0.68 (0.36)
Aggregate constraint	0.70 (0.25)	0.69 (0.26)
Betweenness centrality (thousands)	0.05 (0.18)	0.03 (0.11)
Brokerage (number of positions)	14.94	8.72
Betweenness/brokerage indicator (1 = non-zero value)	0.52 (0.50)	0.40 (0.49)
N = 82,579		

projects, an inventor has at any given time in the network. Aside from those in chemical and health corporations (where women have lower average degree centrality compared to men for many years), the table and graph shows little substantive difference between men and women in this regard – in the aggregate sample, within organizational affiliations, and across time.¹⁷

Inventors' "closeness centrality" to others is evaluated by taking into account the number of geodesic "steps" between themselves and everyone else in the network. On average, women tend to be equal or slightly "closer" to others compared to men, as indicated by their slightly higher average closeness scores, across sectors and time (Fig. 3b). These small differences are likely related to the fact that women are located in clusters with higher size and are less likely to patent alone. Men and women also do not differ greatly in their average "clustering", measured by the extent to which an inventor's collaborators are in turn connected to each other (women's clusters are slightly more dense), or their aggregate constraint, a measure of the (proportional) importance or strength of an inventor's ties to their collaborators, given their collaborator's investment in other ties.¹⁸

The third set of measures represents the point of greatest difference between men and women inventors. Stemming from a long and established line of research built on the idea of the "strength of weak ties" (Granovetter, 1973), network theorists posit that individuals who sit on a high number of "shortest" paths between others in the network (betweenness), and those that connect two otherwise unconnected people (brokerage), have more efficient access to information, enhanced access to new opportunities, and power to constrain others (Burt, 2005). In the innovation context, inventors who are in strategic locations may more easily bring together collaborators that have boundary-spanning knowledge, and may be in particularly unique positions to learn of, build, and/or capitalize on diverse knowledge sources that support combinatory innovative development (Perry-Smith and Shalley, 2003; Uzzi and Spiro, 2005; Fleming et al., 2007; Lingo and O'Mahoney, 2010).

In the aggregate as well as across time and organizational space, women are less likely to be in positions of strategic advantage compared to men (Fig. 3c and d). There is a 45% difference in men's and women's average betweenness centrality, with the largest percent differences between men and women who patent with government agencies (a 79% decrease) and chemical and health corporations (58%). Women in non-profit research hospitals and organizations, DBFs, and

¹⁶ Considering those outside the main component, women also tend to reside in network components that are 10–15% larger than men's, depending on organizational affiliation (results not shown but available upon request).

¹⁷ Similar trends are found using a normalized degree centrality measure (which account for the number of inventors in the network in a given year), and for other organizational affiliations not included in the table (omitted for ease of interpretation). In addition, for all measures in this section, similar trends are found when shifting to a "portfolio approach" for the measures in Table 3; that is, when looking across an inventor's years in the network and computing an average of those averages.

¹⁸ Graphs not shown but are available upon request.

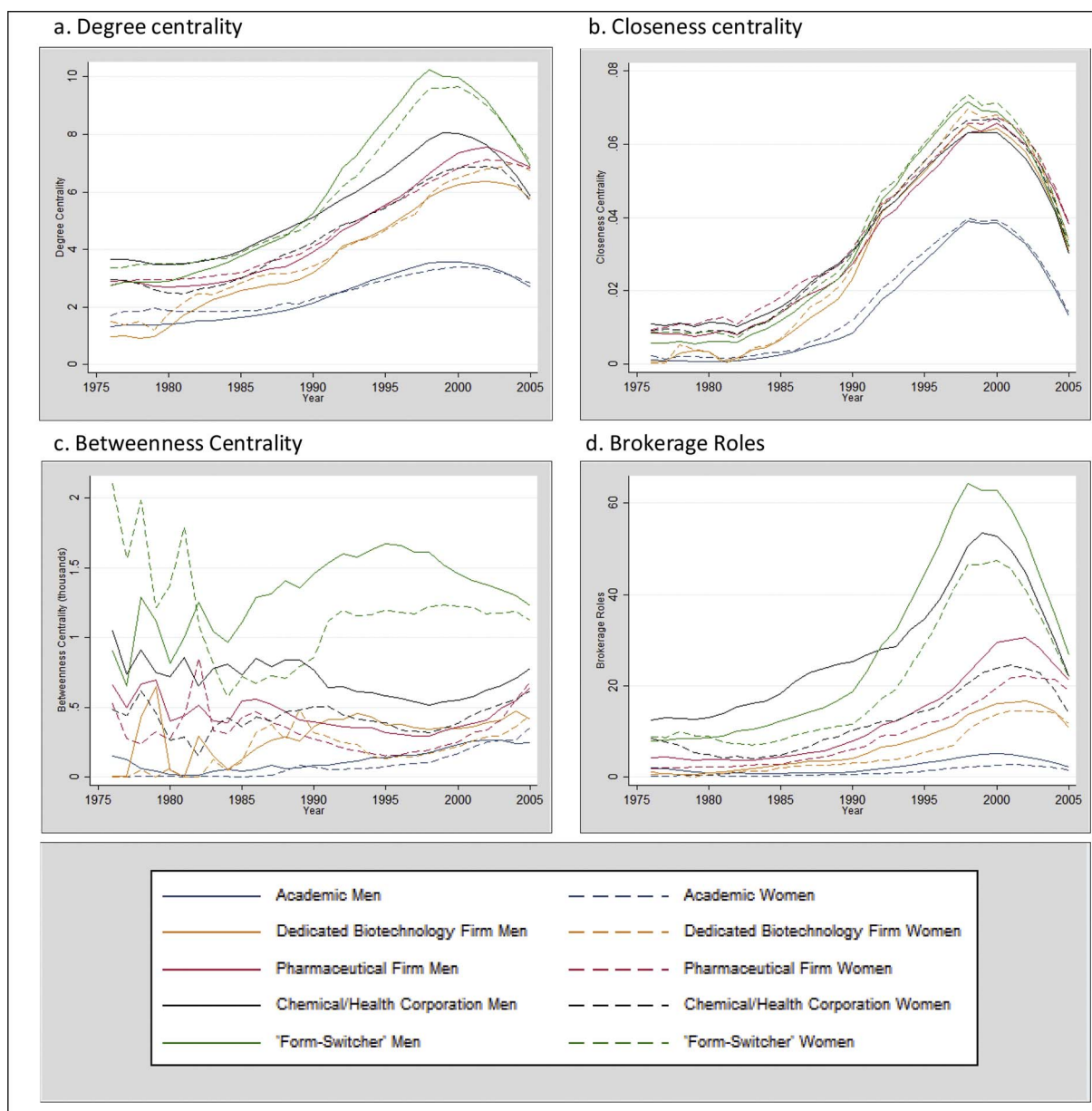


Fig. 3. Men's and women's average network centrality by year and organizational affiliation, 1975–2005.

pharmaceutical firms range have a smaller, yet still significant, difference from men (42–46%). The gender disparity is much smaller among those in universities (19%), although even there women still trail men.

Women also tend to have more redundant ties than men, and are less likely to be in possession of ties to others that do not have ties to each other (brokerage). On average, men hold almost twice the number of brokerage positions than women do across their years in the network (14.7 versus 8.7, respectively, a 52% difference). The percent difference is greatest for inventors in government (93%), chemical and health corporations (69%) and universities (55%); it is least in dedicated biotechnology firms (12%), pharmaceutical firms (19%), and for “form-switchers” (29%).

Much of the difference between men and women in these positions, however, appears to be related to the fact that women are less likely to be in network locations that have any degree of strategic positioning. While only about half of the sample has any degree of brokerage and betweenness (49%), it reduces to 40% for women. Proportionally, women comprise 28% of inventors without any degree of betweenness and brokerage, but only 19% of inventors with a non-zero value. Among those with any amount, the percent difference in betweenness drops to below 10% in DBFs, pharmaceutical firms, and non-profit

research institutions, and below 50% in chemical/health corporations, universities, and government. The disparity is also related to the fact that men are more prominent in the upper tails of the distribution for these two measures. That is, there are disproportionately more men “star inventors” who are prominently and centrally located in the network. A particularly useful focus at this point, then, may be better understanding mechanisms around which women become less likely to gain access to strategic brokerage positions in collaborative work more generally, an implication discussed in more detail later.

Key takeaways from the descriptive results suggest that women follow similar trajectories as men into commercialization, just more slowly, have fewer overall patents, and represent fewer “star inventors” at the high end of the patent count distribution. While they have co-inventors with similar commercial profiles, there are greater asymmetries between their collaborators and themselves in experience and proclivity to patent. Men are more likely to collaborate with other men, and women's collaborative networks include more women; yet men co-inventors make up the majority of inventor's collaborators. Finally, differences in brokerage and betweenness are suggestive of a more peripheral location for women in network positions that maximize

Table 5Maximum likelihood estimates (odds ratios, logit) of patenting ($t = 1$) given inventor demographic and network characteristics ($t-1$).

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10
Inventor Characteristics										
Female Inventor (1 = female)	0.817***	0.943***	0.972***	0.943***	0.925***	0.963***	0.985**	1.021***	0.982**	1.008
Patenting activity in previous year (1 =)	1.812***	1.351***	1.405***	1.685***	1.247***	1.247***	1.247***	1.246***	1.247***	1.246***
Percent US-Based Patents	0.993	1.023***	1.074***	1.013**	1.068***	1.068***	1.068***	1.069***	1.068***	1.069***
Years in the collaboration network	1.000	0.997***	1.003***	1.005***	1.000	1.000	1.000	1.000	1.000	1.000
Core industry inventor (1 = always life science inventor)	0.565***	0.691***	0.633***	0.582***	0.702***	0.701***	0.701***	0.701***	0.702***	0.701***
Organizational Affiliation (1 =)^b										
University		0.848***	0.968***	1.003	0.995	1.048***	1.048***	1.046***	1.048***	1.046***
Pharmaceutical Firm		0.982*	0.934***	0.937***	0.968***	0.920***	0.920***	0.920***	0.920***	0.920***
Chemical and Health Corporation		0.985	0.919***	0.915***	0.963***	0.893***	0.892***	0.891***	0.892***	0.892***
Nonprofit Research Hosp./Institute		0.823***	0.951***	0.973***	0.959***	1.026**	1.025**	1.024**	1.025**	1.025**
Government		0.815***	0.926***	0.905***	0.956**	0.970*	0.969*	0.969*	0.969*	0.970*
Other Biomedical/Biotech Company		0.935***	0.970**	1.030**	1.012	1.028*	1.028*	1.028*	1.028*	1.028*
Multiple Forms (same patent)		0.724***	0.860***	0.790***	0.749***	0.866***	0.866***	0.865***	0.866***	0.865***
“Form Switcher” (across patents)		1.302***	1.067***	1.101***	1.276***	1.019*	1.019*	1.018*	1.019*	1.018*
Network Position (lagged 1 year)										
Brokerage Indicator (1 =)			3.268***			2.319***	2.344***	2.320***	2.319***	2.315***
Female “ ”							0.946***			1.011
Degree Centrality				1.097***		1.054***	1.054***	1.056***	1.054***	1.056***
Female “ ”							0.990***			0.988***
Member of Main Component (1 =)					1.826***	1.074***	1.074***	1.073***	1.081***	1.068***
Female “ ”								0.970***	1.024**	
Constant	0.653***	0.572***	0.430***	0.469***	0.485***	0.411***	0.409***	0.408***	0.410***	0.408***
Number of Observations	984464	984464	984464	984464	984464	984464	984464	984464	984464	984464
Clustered N	82579	82579	82579	82579	82579	82579	82579	82579	82579	82579
Chi-Square	9665.15	41851.41	97000.47	60044.74	52596.88	107656.4	107998.6	107643.5	107762.5	107827.4
Degrees of Freedom	29	41	42	42	42	44	45	45	45	47

Notes:

All models include fixed effects for year; ^a omitted category is “Dedicated Biotechnology Firm”.* $p < 0.10$.** $p < 0.05$.*** $p < 0.01$ (two-tailed).

information transmission and resource opportunities—in particular, more women than men are in positions of complete strategic periphery.

8. The influence of position and collaborator characteristics on innovative outcomes

Although it is commonly accepted that social connections enhance the creative process underpinning scientific discovery, the gendered organization and structure of science may mean that network mechanisms that enhance women’s productivity may differ from that of men. In this section I leverage the longitudinal nature of the data to address the importance of men’s and women’s differential positioning on future patenting and collaborative endeavors, controlling for inventor characteristics, sector- and organizational-level affiliations, and year. By taking this approach I do not attempt to statistically resolve the underlying mechanisms behind network influences or contingencies, or to utilize these models to explain away the gender gap in patenting, both of which require more targeted efforts. Instead, I pay particular attention to the idea that an important first step is to document whether collaborative science spaces reveal network benefits that are contingent on gender (Burt, 1998; Ding et al., 2006; Tinkler et al., 2015), and whether there may be “alternate paths to the same outcome” for women versus men (Ibarra, 1997), as research suggests may be the case. I include measures from each conceptual domain in which network influence may be reasonably expected (e.g. location in the network, reach of ties, and positions of strategy), and focus specifically on constructs where theoretical expectations suggest attention is due—namely collaborator experience and position, homophily, and brokerage.

The modeling strategy is comprised of two separate analyses. The first set of models utilizes the temporal nature of the database to predict how inventor demographic and network positioning in one year influence the probability of patenting in a subsequent year. The second analysis collapses

observations of inventors into a single inventor profile to assess the importance of men’s and women’s *collaborator* characteristics on cumulative patent count. Tables A1 and A2 provide variable correlation matrices for each analysis.

8.1. Network correlates of future patenting

Table 5 presents odds ratios of maximum likelihood estimates from logistic regression models where the unit of analysis is inventor-years, and the outcome of interest is a granted patent at time 1 given network characteristics at $t-1$ years. I utilize clustered (robust) standard errors and fixed year effects to account for repeated measures of inventors across time, and find substantively similar results when incorporating a two- or three-year lag instead. All models include controls for the following characteristics: inventor organizational affiliation; percent of portfolio containing US-based patents (“internationality”); number of years the inventor has been in the collaboration network; whether or not the inventor patented in the previous year (1 = yes)¹⁹; number of unique organizational identities or affiliations to which the inventor has been linked; and whether or not the inventor is “always” (or only “sometimes”) a “core” life science inventor (1 = yes). Following on the heels of the descriptive analysis, I turn my focus to three primary network measures for inclusion in the model sets – 1) degree centrality, 2) an indicator variable for (non-zero) brokerage (betweenness)

¹⁹ Readers may be interested in the possible influence of temporal dynamics with respect to the model results. In sensitivity analyses not presented here, models with alternative configurations of the “years in the network” control variable, including year dummies or categorical specifications for the time since last patent, and year dummies or categorical specifications for the time since last patent, do not reveal substantively different model coefficients or predicted effects, and all conclusions remain the same. I draw the same conclusions for models that do not include a variable for whether or not an inventor patented in the previous year.

Table 6
Predicted odds of patenting for selected interactions (Model 10, Table 5).

6a. Gender and Brokerage	
Male Non-Broker	0.31
Female Non-Broker	0.30
F/M ratio	0.96*
Male Broker	1.96
Female Broker	1.23
F/M ratio	0.63***
6b. Gender and Main Component (MC) Location	
Male, not in MC	0.39
Female, not in MC	0.33
F/M ratio	0.85***
Male, in MC	1.40
Female, in MC	0.75
F/M ratio	0.53***

Notes:

*** (p < .01).

* (p < .1).

positioning, and an indicator variable for location in the network main component (yearly). I include each variable separately and together (Models 3–6), and as a set of interaction variables with inventor gender (Models 7–10). The final model is best fitting and is the model for which all interpretations are derived.

The models show the odds of patenting activity increase as a scientist's embeddedness in the networks grows, controlling for inventor characteristics, prior experience and year. Furthermore, the models show that there are statistically relevant interaction effects between gender and network position, suggesting that gender may moderate the influence of embeddedness on inventors' future activity. While the interaction between gender and brokerage loses significance in the final model (as does the baseline effect of being female), statistically appropriate conclusions from interactions in logistic regression can only be made when considering marginal or predicated probabilities (calculations of the difference of differences in probabilities) (Buis, 2010). Table 6 presents the marginal effects of the odds of patenting for both brokerage and membership in the main component, holding all other variables within group at their observed values. In the case of brokerage, the final model reveals no gender differential in the odds of patenting between men and women who lack a brokerage position. For non-brokers, the baseline odds of patenting in a future year for men and women are 0.31 and 0.30, respectively. However, while men and women both experience a significant boost to these odds when in brokerage positions, the odds of patenting for women brokers are 0.63 that of men brokers. This suggests that women's brokerage locations are not as predictive for future patenting activity as are men's.

A similar result is found in the marginal calculations for the influence of holding a location in the network "main component". While both men and women benefit being in this hub of activity, men benefit significantly more so than women. In this case, women's predicted odds of patenting when in the main component are 53% that of men who are in the same location. Men and women who are not in a main component in a previous year are closer in their predicted odds of patenting (0.39 versus 0.33, respectively) than men and women who are more centrally located.

Despite the statistically significant interaction effect between the variables for gender and degree centrality, there are no substantively revealing differences between men and women in the network benefits they receive from increasing ties to additional collaborators. In a graph of the predicted odds of patenting, as degree centrality rises from 1 to 25 (not shown), the effect on women's patenting compared to men is reduced by only 0.06 patents (n.s.). Similar (non-)effects were found in sensitivity analyses utilizing alternative measures in the models that relate to degree, such as closeness centrality, the clustering coefficient, and measures of aggregate constraint.

A final consideration relates to our understanding of the influence of network versus non-network characteristics on the probability of patenting for men and women in the life science commercial network. Although it is not appropriate to compare the direct effect for gender across the set of non-linear nested models, model fit statistics suggest that both network and non-network characteristics shed light on inventor propensity to patent in the life sciences. Each nested model improves in fit; and models that isolate network and non-network variables contribute independently to this fit.²⁰ In the baseline model (Model 1), the predicted odds of patenting for men are 0.55 and 0.45 for women (when all other variables are held at their observed value). The inclusion of non-network variables (Model 2) reveals predicted odds of 0.59 for men and 0.55 for women, suggesting that these characteristics serve to decrease the gap. The final, fully specified model that adds network variables predict the odds of men patenting to be 0.89, and that of women 0.70 (Model 10).²¹ These results provide support for previous work that emphasizes the strength of "sorting" dynamics (such as women's differential rates of participation across science fields) in explaining aggregate differences between men's and women's innovative activity in science (see, for example, Hunt et al., 2013). While sorting effects (and other non-network characteristics) can help us understand how differences in men's and women's experience, international reach, and distribution across types of institutions play a role in the gender gap in propensity to patent, the results of the final model suggest that there are still differences in men's and women's propensity to patent despite controlling for these and network measures. The likelihood of patenting again is high, and well-positioned network relationships benefit everyone's odds of patenting. Yet men's differential rewards result in findings of greater average disparity between men and women after network positioning and tie influence is taken into account.

8.2. Collaborator benefits towards future patenting

In the second analysis, in order to examine the influence of collaborator characteristics I collapse yearly records over time to convert the sample from one where the unit of analysis is inventor-years to that of cumulative inventor profiles over time. The sample now includes all inventors that have at least one collaborator (N = 78,066). These models utilize the total patent count in an inventor's portfolio as the dependent variable, and incorporate a negative binomial count modeling strategy because of overdispersion in the outcome variable.²² Table 7 presents incidence rate ratios from a series of nested models that include measures for inventor's collaborator's experience (average years in the network), productivity (average number of patents), and connectedness (average degree centrality, brokerage, and frequency of location in the main component). The models also include a measure of collaborator homophily, calculated as the proportion of an inventor's collaborators who are women (1 = all women co-inventors). All measures for collaborator characteristics are constructed by taking the average of the collaborator values, although findings related to gender differentials and interactions are similar when the measures are constructed to reflect status asymmetries between inventors and their collaborators.

Like the first set of models, increases in model fit across the set underscore the importance of both network and non-network influences in understanding commercial activity. While each represent a significant proportion of the variation, collaborator characteristics can be seen to exert a smaller (yet independent), influence on inventor

²⁰ Models with network variables only (not shown) reveal a model fit of $\chi^2 = 84,675.70$ (35).

²¹ A comparison model with network variables only (not shown) reveals predicted odds of 0.90 for men and 0.65 for women.

²² Similar results and conclusions are revealed from an alternative modeling strategy that incorporates zero-truncated negative binomial count modeling to account for the non-zero characteristics of the data.

Table 7

Negative binomial incidence rate ratios of inventor's total patent count given collaborator and inventor characteristics.

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Inventor Characteristics							
Female Inventor (1 = female)	0.628***	0.944***	0.961***	0.974	0.914***	0.930***	0.883***
Percent US-Based Patents (1 = all US)		1.091***	1.064***	1.063***	1.062***	1.066***	1.065***
Inventor years in collaboration network		1.093***	1.087***	1.087***	1.087***	1.087***	1.087***
Organizational Affiliation^a							
University		0.945***	0.966***	0.966***	0.967***	0.965***	0.966***
Pharmaceutical Firm		0.914***	0.954***	0.955***	0.954***	0.954***	0.953***
Chemical/Health Organization		0.993	0.981**	0.981**	0.981**	0.978**	0.979**
Non-Profit Research Hospital or Institute		0.893***	0.949***	0.950***	0.950***	0.949***	0.950***
Government		0.865***	0.939***	0.940***	0.940***	0.938***	0.939***
Other Biomedical/Biotech Company		1.064	1.030*	1.031**	1.030**	1.027*	1.027*
Multiple Forms (same patent)		0.819***	0.852***	0.854***	0.853***	0.851***	0.854***
Form Switcher		0.983	1.013	1.014	1.014	1.013	1.013
Number of Unique Institutional Affiliations		1.004	1.004	1.004	1.004	1.004	1.004
Inventor Connectedness							
Degree Centrality		1.067***	1.090***	1.090***	1.090***	1.090***	1.090***
Brokerage Indicator (1 = always broker)		1.950***	1.817***	1.816***	1.815***	1.817***	1.815***
Main Comp. Location (1 = always in MC)		0.931***	0.875***	0.874***	0.874***	0.875***	0.874***
Collaborator Characteristics							
Collaborators # Unique Affiliations (avg)			0.992	0.996	0.992*	0.993	0.997
Female " "				0.985*			0.981**
Collaborators # of Patents (avg)			1.023***	1.023***	1.023***	1.023***	1.024***
Female " "				1.001**			0.999
Collaborators # of Yrs in Network (avg)			0.984***	0.984***	0.984***	0.984***	0.983***
Female " "				1.000			1.001
Collaborator Connectedness							
Collaborators Degree Centrality (avg)			0.928***	0.928***	0.926***	0.928***	0.926***
Female " "					1.006***		1.007***
Collaborator Brokerage (avg)			1.394***	1.394***	1.392***	1.393***	1.383***
Female " "					1.011		1.034
Collaborators Always in Main Comp. (avg)			1.302***	1.303***	1.311***	1.302***	1.314***
Female " "					0.985		0.975
Collaborator Homophily							
Collaborator Percent Female (1 = all female)			1.009	1.008	1.01	0.965***	0.964***
Female " "						1.139***	1.141***
Constant	8.703***	0.786***	0.930***	0.927***	0.940***	0.937***	0.947***
Sample N	78066	78066	78066	78066	78066	78066	78066
Chi-Square	–243125.00	–193861.23	–188448.32	–188444.38	–188434.10	–188430.29	–188412.47
Degrees of Freedom	1	15	22	25	25	23	29

Notes:* $p < 0.10$.** $p < 0.05$.*** $p < 0.01$ (two-tailed).^a Omitted category is "Dedicated Biotechnology Firm".

productivity as well. Model 7 includes all variables together, and is best fitting.

The models characterize several significant main and interaction effects of collaborator characteristics on the outcome variable; in particular, collaborator brokerage and collaborator positioning in the main component are positively associated with inventor productivity, for both men and women. In contrast, there is a negative relationship between inventor's patent count and being tied to many collaborators who have many co-inventing ties themselves—that is, inventors that are tied to those with fewer co-inventors tend to have more patents in their portfolio. It is possible that this may relate to typical divisions of labor in laboratory science—with technicians and other support staff represented periodically on patents associated with PIs that have many collaborators. This may also relate to notions that cohesion and strong ties can lead to innovative redundancy for inventors (Fleming et al., 2007). Although the relationship holds for women as it does for men, there is a slight, substantively small, reduction in the negative association for women compared to men.²³

The model results suggest that gender homophily supports patent

productivity for men and women. Fig. 4 takes into account the direct and interactive effects of gender and homophily and presents the gender difference in predicted patent count as the proportion of collaborators who are women increases. All else equal, women with all male collaborators are predicted to receive one fewer patent (1.03) than men who have all male collaborators. In contrast, when all collaborators are women, women are predicted to receive nearly one (0.85) patent more than men who have all female collaborators. Although the reasons for homophily in this context likely depend on a variety of factors, including status-based influences as well as gendered sorting mechanisms related to job positions, subfields, and roles (West et al., 2013), the implications are that both men and women benefit from gender homophilous ties. Despite the benefits, that there are far fewer women are in the network than men may translate into substantial disadvantage to women.

Out of the remaining six interactions between inventor gender and collaborator characteristics, calculations of the marginal effects reveal that most have little gender differentiation in influence. These include: the influence of the average number of years collaborators are in the network, the average collaborator cumulative patent count, and the number of unique organizational affiliations collaborators have. In

²³ Predicted values not shown but available on request.

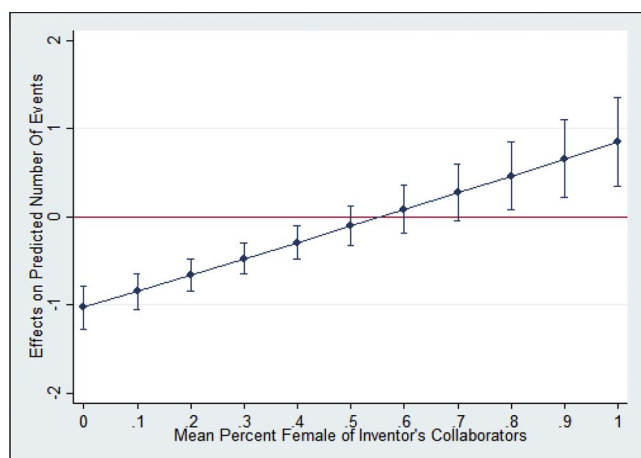


Fig. 4. Women's predicted patent count compared to men as proportion of collaborators who are female rises (0 = all male collaborators; 1 = all women collaborators), holding all other variables at their observed values. (Table 5, Model 7).

contrast to the previous set of models, which finds that gender moderates the influence of brokerage, *collaborator* brokerage—that is, the extent to which an inventor's co-inventors are strategically well-connected—is also not significantly different in influence for men and women.

9. Discussion

Past work on gender disparities in science has proposed many potential mechanisms for women's differential participation in commercial science, and these include complex interactions between supply- (e.g., human and social capital) and demand-side (e.g., opportunities to participate) influences (Murray and Graham, 2007; Stephan and El-Gainainy, 2007). Scholars have not ignored the fact that network influences on collaborative activity may underscore many of these dynamics (Hunt et al., 2013), yet gaining access to these in an analytically fruitful way has been challenging. Focusing on the case of patenting in the life sciences, the data at hand provides an opportunity to examine myriad ways in which women are positioned in the social structure of commercial science compared to men, and whether network benefits are contingent upon or moderated by gender in this collaborative space.

This research finds that women's similarity with men regarding collaborative positioning and rewards to connectedness is uneven. When centrality is conceptualized as an abundant number of close ties and the availability of others within reasonable reach, there are only subtle differences in the positioning of women and men inventors in the sample. The results show that women inventors are not more peripheral in terms of their close ties and access to indirect others, nor that they are located amongst less dense subsets of ties (clustering) or to those for whom their ties are “less important” (aggregate constraint). As expected, however, a focus on collaborative networks reveals substantial differences between men and women with respect to their strategic positioning among other inventors. Most notably, women are much less likely to collaborate in positions traditionally thought to lead to added innovative benefits—positions that hold brokerage opportunities. In addition, men tend to include more men in their collaborations, women more women, and women have more status-asymmetric ties. Given that the network is comprised of scientists who all have at least one patent, and that scientists involved in commercial activity are a minority in the life science population, we might expect these similarities and differences to be at the low end of what we would see if able to take into account the positioning of those not (yet) involved in commercial life science.

The results also reveal evidence that some network benefits may be contingent on gender, and imply that we cannot assume, both in theory

or in practice, that the association between collaborative positioning and innovation is similar for men and women. This is true particularly with respect to the influence of strategic positioning, of being in the main “hub” of network activity (i.e. the main component), and also regarding the prevalence and influence of gender-homophilous ties.

It is useful to consider the implications of these findings against the backdrop of previous work on this topic. Previous work has found little difference in the scientific *quality* men's and women's work, including in patenting and other commercial endeavors (Whittington and Smith-Doerr, 2009). This has led scholars to suggest that increasing the number of women involved in scientific activity is thus tied to increasing the quality of scientific capacity more generally. Furthermore, greater diversity among creators of science and technology tends to lead to better knowledge and products (e.g. Jehn et al., 1999). Accordingly, diversity and gender equity are seen more and more on the agenda of global forums, and in the mission statements of funding agencies and public and private institutions. The focus of this research dovetails with that of those looking to understand the effects of diversity on collaborative endeavors, and well as diversity and inclusion initiatives. If women inventors are involved in more diverse networks of collaborations (at least in terms of gender-homophilous ties), the implication is that women may be more likely to bring other women (and new ideas) into the commercial context. A tendency towards homophily and gender-homophilous benefits, however, may disproportionately stifle women inventors when there are far fewer women in the collaborative space more generally. Attention to building men's and women's communication and cooperation, towards balancing gender representation in research teams and policy and decision making groups, and to sustaining careers (especially, women's advancement in the discipline), may help improve innovation and research quality as it relates to these findings.

The policy implications of this research are further underscored by the increasing importance being given to data such as this as an evidence base for policy-making. Quantitative data provides policy-makers with evidence for the persistence of social inequalities, and aids in the determination and articulation of best approaches. In this, there is a need for better clarity around the mechanisms by which women are less likely to gain access to and benefit from strategic positions. It remains a question for future research whether the differences between men and women arise from issues of underrepresentation or social differences more generally, and may include: the *types* of connections men and women have (that is, how ties come to fruition and in what context); the ways in which women and men extract downstream resources from their connections; the availability of collaborators in one's immediate network; and/or from other, not yet specified, mechanisms related to men's and women's network locations. While there is evidence of progress, this analysis provides a road map for areas in need of specific attention.

Furthermore, if women have less access to and knowledge of the commercial process, as Murray and Graham (2007) find, greater attention to fostering networks of relationships within organizational settings could improve women's involvement. Some suggest that Technology Licensing Offices (TLO) provide just this kind of institutional support, and that this may be why women's patenting in the university setting has increased (Sugimoto et al., 2015). One study of academic faculty in three Academic Health Centers finds employment context and resources to be tantamount in supporting women's involvement in commercial endeavors (Colyvas et al., 2012).

The focus of this case is on just one of many possible innovative activities, and it would be helpful to know more about predictors of collaborative relationships before the patenting application process occurs, and in collaborative relationships that do not result in a granted patent or product. Future research should also examine network data that includes collaborative ties beyond the commercial realm, such as publishing relationships, and/or social capital relations accrued through other aspects of the science career, such as through the labor

market. Women may be more or less likely to be poorly positioned in commercial networks compared to publication networks, for example, or may (differentially) gain from non-commercial linkages in their research networks. It would be useful to know the extent to which network effects interact with additional job- and individual-specific characteristics, and to compare the relative size of within- versus between-person effects.

Finally, although the organizational level is not the primary focus of the analysis, this work suggests that the greatest gender disparities in collaborative activity appear in industry science, specifically among inventors in large, multi-national health-related firms and in pharmaceutical companies. Although the nature of the disparity varies across measures and is not uniformly present across all years, the broad trend may be due to the fact that multi-national firms patent more and are also distributed more broadly globally (where gender disparities may be more pronounced). It may also be due to differences in women's likelihood of working in corporate R&D. A final factor may be related to the incentive structure and logic of organizing in these firms. Collaborative settings and those with a more horizontal distribution of work relations (such as that of dedicated biotechnology firms and in academia) may boost women's integration and have been shown to be more gender equitable in terms of leadership positions (Smith-Doerr, 2004) and in patenting and publishing productivity (Whittington and Smith-Doerr, 2008; Sugimoto et al., 2015). Future attention to the organizational antecedents of women's performance in science is sorely needed, both for the research insights such comparisons can illuminate

but also for greater understanding of the experiences of the high percentage of men and women who work outside of the academic science setting.

Understanding how network relationships underscore productivity rates, and other performance differentials, is important in order to assess—and help redress—gender differences in rewards because these are partially explained by productivity (Fox, 1999; Long, 2001; Sonnert and Holton, 1995).²⁴ If, as Powell and Padgett state, “In the short run, actors create relations; in the long run, relations create actors” (2012, p. 2), these critically important network antecedents have implications not only for women's careers, but for the production of knowledge and innovation in the scientific market as well.

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Appendix A

Table A1

Correlation Matrix of Inventors Characteristics, Network Panel (Table 5, N = 82,579).

	1	2	3	4	5	6	7	8	9
1. Inventor Patenting Activity (1 =)	1								
2. Inventor Patenting Activity, Lagged 1 Year	0.164	1							
3. Percent US Based Patents	0.002	−0.002	1						
4. Years in Patenting Network	0.072	0.161	0.004	1					
5. Core Life Science Inventor (1 =)	−0.143	−0.141	−0.009	−0.291	1				
6. Female (1 =)	−0.031	−0.035	−0.069	−0.111	0.160	1			
7. Main Component Location (1 =), lagged one year	0.165	0.171	−0.055	0.102	−0.039	0.060	1		
8. Brokerage Indicator (1 =), lagged one year	0.313	0.319	−0.027	0.203	−0.249	0.057	0.407	1	
9. Degree Centrality, lagged one year	0.276	0.282	−0.074	0.159	−0.138	0.004	0.427	0.545	1

Table A2

Correlation Matrix for Characteristics of Inventors and their Collaborators, Collaborator Panel (Table 7, N = 78,066).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Inventor Patent Count	1														
2. Inventor Female (1 =)	−0.094	1													
3. Inventor Percent US Based Patents	0.000	−0.036	1												
4. Inventor Years in Patenting Network	0.479	−0.167	0.022	1											
5. Inventor Number of Unique Organizations	0.230	−0.044	0.063	0.293	1										
6. Inventor Mean Brokerage	0.364	−0.114	0.002	0.467	0.269	1									
7. Inventor Mean Degree	0.492	−0.003	−0.067	0.120	0.218	0.401	1								
8. Inventor Mean Main Component Location	0.012	0.086	−0.054	−0.228	−0.036	0.048	0.367	1							
9. Collaborator Mean Gender	−0.025	0.172	−0.064	−0.062	0.027	−0.015	0.057	0.012	1						
10. Collaborator Mean Unique Organizations	−0.022	0.041	0.101	−0.020	0.372	−0.024	0.019	0.163	−0.021	1					
11. Collaborator Mean Patent Count	0.226	−0.014	−0.009	0.127	0.020	0.151	0.210	0.284	−0.093	0.242	1				

(continued on next page)

²⁴ “Partially” is a key term. The extent to which productivity governs rewards is a recurring debate (e.g., Ceci et al., 2014), and metrics of performance are infused with considerations of gender and dimensions of inequality. Further, women's records of performance do not automatically translate into rewards and recognition equivalent to men's (Wennerås and Wold, 1997).

Table A2 (continued)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
12. Collaborator Mean Years in Patenting Network	0.133	−0.036	0.019	0.221	0.024	0.114	0.042	0.139	−0.172	0.298	0.498	1			
13. Collaborator Mean Degree	0.192	0.041	−0.084	0.062	0.072	0.240	0.621	0.511	0.010	0.220	0.611	0.238	1		
14. Collaborator Mean Brokerage	0.156	0.004	0.011	0.132	0.036	0.238	0.221	0.321	−0.119	0.259	0.430	0.553	0.469	1	
15. Collaborator Mean Main Component Location	0.206	0.012	−0.092	0.083	0.093	0.292	0.507	0.655	0.022	0.077	0.314	0.070	0.646	0.343	1

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