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Regional co-evolution of firm population, innovation and public research? Evidence from the West German laser industry

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ABSTRACT

We trace the co-evolution of regional firm population sizes, private-sector patenting and public research in German laser research and manufacturing for over 40 years from the emergence of the industry to the mid-2000s. Qualitative as well as quantitative evidence suggests a co-evolutionary process of mutual interdependence rather than a unidirectional effect of public research on private-sector activities.

1. Introduction: The paradox of the linear model

The linear model of innovation posits that innovation proceeds in a unidirectional sequence from basic research over applied research and industrial development to product or process innovation[1]. There is broad consensus among innovation scholars that the linear model is incomplete because it neglects relevant feedback from "later" (i.e., closer to product development) to "earlier" stages. In this paper we provide historical and quantitative evidence indicating that this feedback is important in the regional co-evolution of industry, innovation, and public research.

Various theoretical contributions address the limitations of the linear model. The chain-linked model of innovation (Kline and Rosenberg, 1986) accounts for the often complex interactions between public research and industrial research and development (R&D). Stokes' (1997) notion of Pasteur's Quadrant highlights that the boundary between basic and applied research can often not be drawn in a meaningful way. The systems of innovation approach emphasizes the importance of science-industry interaction at various geographic and sectoral scales. This approach played an important role in conceptually discrediting the linear model (Fagerberg, 2003). And from the perspective of industry evolution, it has been suggested that public research is a key element of the "institutional context" that an industry co-evolves with (Nelson, 1994).

Substantial empirical evidence likewise points to shortcomings of the linear model. For instance, private-sector R&D managers report that public research is equally important to them in solving problems that emerge in ongoing R&D projects as it is in inspiring new R&D projects (Cohen et al., 2002). Other research has found that the commercialization odds of university inventions licensed by private-sector firms are higher when university inventors actively support the post-licensing innovation efforts (Agrawal, 2006).

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[1] The linear model is conventionally attributed to Bush (1945), who was then serving as the director of the U.S. Office of Scientific Research and Development. According to Stokes (1997), Bush himself may not have believed in the linear model. Instead, he may have used it as a rhetorical device to justify sustained public funding of basic research after the end of World War 2.

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These theoretical and empirical contributions notwithstanding, it is widespread practice in empirical studies to estimate the importance of unidirectional knowledge flows from public research to industrial R&D without allowing for reverse causality. Thus, while the linear model is rarely explicitly defended by innovation scholars, it implicitly underlies a large number of empirical research designs. This is what we refer to as the paradox of the linear model. Examples can be found in various empirical contexts. For instance, a number of studies show that public research activities help explain regional rates of innovation (e.g., Feldman, 1994; Leten et al., 2014) or new firm formation (e.g., Audretsch et al., 2005; Fritsch and Aamoucke, 2013) without addressing potential influences from innovation or entrepreneurship on public research. The same can be said about studies of industry evolution that consider public research as a determinant of regional entry rates (e.g., Stuart and Sorenson, 2003; Buenstorf and Geissler, 2011)[2].

That the potential impact of private-sector activities on public research is often eclipsed in empirical research is all the more puzzling because historical evidence clearly suggests its relevance. Historians of science and technology have long argued that new scientific disciplines often emerge from the quest to better understand the foundations of recent technological advances (cf., e.g., Rosenberg, 2004). Commercial firms may actively push for the scientific investigation of phenomena relevant to their products and processes. For instance, in the context of the historical synthetic dye industry Murmann (2003; 2013a,b) has shown how producers in the laggard German industry leveraged their close interaction with university chemists to attain world market leadership.

The prior discussion of how science and technological innovation interact has mostly focused on the aggregate level. Our principal interest in the present paper relates to the more mundane level of regional interdependence and co-evolution, which we expect to be driven by the activities and initiatives of various regional actors such as firms, universities or individuals. It is not hard to find prominent examples illustrating how regional interaction led to the co-evolution of science and private-sector innovation activity. For instance, Akron, Ohio, had long been the center of the U.S. rubber and tire industry when in 1908 the University of Akron started to engage in rubber research. Historical sources show that the move into rubber research was strongly supported by the local rubber firms[3]. Today, the University of Akron College of Polymer Science and Polymer Engineering claims to be "the largest academic program of its kind in the world" (http://www.uakron.edu/about_ua/history; last accessed December 8, 2015). The university is a key player in the region's efforts to position itself as "Polymer Valley" and to be a leading location for research and production in the fields of polymer research, rubber, plastics and advanced materials. And while the large rubber and tire companies have mostly disappeared from Akron, the 2010/2011 *Directory of Polymer Industries* published by the Greater Akron Chamber of Commerce lists more than 200 polymer establishments in the region.

It is this kind of regional co-evolution of science, innovation, and industry that we focus upon in the present paper. Using German laser research and manufacturing as our empirical context, we trace regional science-industry interaction and the co-evolution of regional firm populations, innovation activities, and public research over a 40-year period from the emergence of the industry to the mid-2000s. Based on a review of qualitative work as well as quantitative analyses, our evidence suggests a co-evolutionary process of mutual interdependence rather than a unidirectional effect of public research on private-sector activities. To the extent that this finding generalizes beyond the specific empirical context, it has potentially far-reaching implications for empirical research on science-industry interaction, but also for innovation policy and firm strategy.

The paper is structured as follows: The following section reviews prior findings on co-evolutionary dynamics in innovation systems. Section 3 presents results from historical research as well as some descriptive patterns on the evolution of laser research and manufacturing in Germany. The econometric analysis is in the focus of Section 4. Section 5 concludes.

2. How does public research affect regional industry activities—and vice versa?

2.1. Co-evolution of public research and private-sector R&D

Co-evolution has been suggested as a theoretical framework to account for interdependent dynamics of industry, technological change, and the institutional environment (Nelson, 1994; Murmann, 2003). The defining characteristic of co-evolving populations is that changes in each population have causal effects on the subsequent evolution of the other population(s). The co-evolution concept resonates with the systems of innovation approach highlighting the interactive nature of innovation processes (e.g., Lundvall, 1992; Nelson, 1993; Malerba, 2002; Cooke et al., 2004; cf. also Soete et al., 2010, for a survey). According to this approach, the performance of innovative firms is shaped by their interactions with a wide range of other actors including customers, suppliers, universities and public research organizations. It is also conditioned by the institutional context, including the prevailing policy and regulatory framework as well as cultural, scientific and technological traditions.

Finding evidence of co-evolutionary dynamics within innovation systems would provide empirical support to the systemic approach to innovation. The analysis of co-evolutionary processes also helps address limitations of current empirical work in the systems of innovations literature (cf. Fagerberg, 2003; Castellacci, 2007). In particular, even though the systemic view of innovation originated within evolutionary economics, the population thinking characteristic of evolutionary economics is often absent in the work on innovation systems. Instead of investigating micro-level actors such as individual firms, empirical research based on the systems of innovation approach frequently focuses to broad aggregates. Relatively little is also known about the evolutionary dynamics of innovation systems.

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[2] Note that the seminal empirical contribution by Jaffe (1989) allowed for, but did not find, an effect of industrial R&D on public research activities at the level of U.S. states.

[3] B.F. Goodrich started the Akron rubber industry when he moved his New Jersey firm there in 1871. Goodrich pioneered the market for automobile tires in the early 20th century. Jointly with local competitors Firestone and Goodyear (as well as U.S. Rubber from Detroit) it soon dominated that industry. In 1908, the Municipal University of Akron established a course in rubber chemistry, apparently the first and for a long time only course of this kind at a U.S. university (India Rubber Review, 8/1922). In 1915, William F. Zimmerli, Ph.D., then in charge of the Chemistry department at the University of Akron, writes in the trade journal *India Rubber Review* about the department's course in rubber chemistry: "I have met hearty encouragement and assistance from all branches of the rubber industry." Specifically, he notes that rubber dealers provided him with samples, that Goodyear engineers helped him design the rubber laboratory, and that he purchased laboratory equipment at reduced prices from a local rubber machinery maker. In 1922, his successor, Professor H.E. Simmons, similarly writes: "The industries of the city co-operate to the fullest extent, enabling our students to get actual experience in manufacturing from the practical standpoint as well as from the theoretical. In return for these courtesies extended to us by the factories of Akron we try to be of service to them in whatever way possible. In fact, some of the smaller companies who do not feel able to go to the expense of equipping a laboratory and hiring a man to have charge of it send their work to the University, and it is taken care of at a small yearly cost to them" (Simmons, India Rubber Review, 1922). Mowery et al. (2004) argue that U.S. universities historically tended to be dependent on resources and support from the local private sector. They also point to Akron as a case in point.

In the present paper, we begin the empirical analysis of co-evolutionary dynamics with a focus on public research, which constitutes an important element of contemporary innovation systems. The most fundamental co-evolutionary process in this context is that between the overall state of knowledge in scientific disciplines and the level of technological development in related industries. It is well known that scientific advances often enable technological innovations. Around the world, technology transfer activities of universities and other public research organizations are increasingly in the focus of public policy makers intent to maximize the societal impact of science. Although less prominently discussed in public, the relevance of reverse causality – technological change driving advances in science – has long been highlighted by historians of science (Mokyr, 2002; Rosenberg, 2004). "Technology oriented sciences" (Nelson, 1994) and new fields of engineering often come into existence because already functioning technology is insufficiently well understood. New technology thus provides the impetus for scientific research. In turn, by adding to the understanding of the respective technology, the work of these new fields and disciplines helps broaden the "epistemic base" (Mokyr, 2002) of the technology, which facilitates future improvements as well as new applications. Research in these technology-oriented fields of science and engineering may directly shift the technological frontier or enable those working in industrial R&D laboratories to do so.

Public research and private-sector innovation are linked through a variety of conduits. Direct ties are established through collaborative and sponsored research. Both public policy makers and private initiatives may help institutionalize such ties through the establishment of research centers focusing on applied research. Short of direct collaboration, firms may access the results of public research that are codified in publications and patents. Knowledge is also transferred when university-educated students and researchers migrate from public research to the private sector. Furthermore, besides contributing to the knowledge base of incumbent firms, public research may also facilitate new entry into an industry (Nelson, 1994). Collaborating with public research enables firms from other industries to diversify into the target industry. In other cases, university researchers become academic entrepreneurs and enter the industry with their ventures (Audretsch et al., 2005).

Firms in technologically advanced industries not only benefit from public research in related fields and disciplines. Many firms spend substantial amounts of their own money to advance science. Ever since the ascent of the corporate R&D laboratory (Hounshell and Smith, 1988), large firms have engaged in basic research activities. Perhaps the most extreme case in history were the Bell Labs, from which several of the key inventions of the 20th century emerged (Gertner, 2012). Nelson (1959) provides an early rationale why larger firms have stronger incentives to engage in such activities, which are plagued by substantial uncertainty about potential fields of application, than their smaller competitors. More recent contributions (Hicks, 1995; Stern, 2004) argue that engaging in basic research activities and publishing results via the traditional outlets of public research allows firms to reap various benefits from signaling their legitimacy to university collaborators to attracting research-oriented employees.

Firms and industry associations also engage in various activities that help researchers and universities. In addition to direct funding, lobbying on behalf of related research is another important activity in this context. Often via industry associations taking the role of intermediaries, firms lobby for public funding of research in the respective fields. Stressing their need for talent, they also lobby for public funding of higher education suitable for their needs. Particularly in the case of new industries, this may include the argument that entirely new programs and possibly even new organizations (e.g., new universities or government laboratories) are required to safeguard the future of the industry and the competitiveness of the respective jurisdiction.

The relevance of these channels of interaction between firms and public research is shown by Murmann (2003, 2013a,b). Murmann provides a detailed account of industry-science co-evolution in the historical context of the global 19th century synthetic dye industry. The role of labor mobility between public research and the private sector is highlighted in this account. Academic entrepreneurship was particularly important at the outset of the industry, to the extent that according to Murmann (2013a, p. 69) the "list of early entrepreneurs in the British synthetic dye industry reads like an alumni directory of the Royal College of Chemistry in London." Established businesses also benefited from hiring talented university scientists, among others because these were embedded in networks through which relevant knowledge could be communicated across firm boundaries. Murmann's account of mobility from industry to public research is also noteworthy. He argues that this type of mobility transferred important new ideas and methods to universities and enhanced their research productivity. It also helped university researchers establish commercial ties to firms. These ties provided them with knowledge as well as physical and financial resources that could be leveraged in the generation of new results and in the scientific competition with other researchers.

The insights from Murmann's historical case study resonate with quantitative findings on the research productivity of present-day scientists. A large number of individual-level studies find that quantity and quality of research output tend to increase with (moderate levels of) industry engagement (among others: Breschi et al., 2008; Azoulay et al., 2009). To account for these patterns, scholars often refer to the inflow of money from collaborating with private-sector partners, which allows university researchers to hire additional staff and invest in new equipment. Access to the superior equipment of industry partners is also credited as an important factor underlying the performance effects of collaborations. Perhaps most relevant, however, are the "reverse" knowledge spillovers from industrial R&D to public research. Problems that firms encountered in the R&D process have long been suggested as powerful drivers of advances in public research (Mansfield, 1995).

2.2. Co-evolution in regional systems of innovation?

The interaction of public research and private-sector R&D has a strong regional dimension. Extant empirical research suggests that knowledge flows between various types of entities, including those from universities to private-sector firms, are more pronounced at shorter geographic distances (Jaffe, 1989; Jaffe and Trajtenberg, 1996). These patterns may result from a number of underlying processes. Geographic distance is an impediment to labor mobility, which reinforces the localized character of social networks in which knowledge is exchanged. Random encounters enabling knowledge transfer between individuals who are not otherwise connected are also more likely within regions. In addition, it is straightforward that both university researchers and private-sector firms tend to focus on regional collaboration partners. Co-located partners are less costly to interact with and may be trusted more not too leak information to third parties.

Based on these considerations, it can also be expected that firms and private-sector associations actively try to shape the research agendas of regional universities and attract relevant research centers (or individual researchers) to their own region. In a given industry context, there are typically smaller numbers of interested firms in the region than there are at the national level. Accordingly, firms will typically have stronger incentives to spend their own money (because less of it spills over to competitors). It is also likely that individual firms or private-sector associations have stronger political clout at smaller geographical scales. Accordingly, they will be able lobby regional policy makers more effectively than national policy makers.

In turn, universities and other public research organizations have much to benefit from the political support of regional firms. It is in their interest to emphasize their importance for regional development and to signal their commitment by codifying regional development objectives. This may be particularly important for public universities dependent on continued funding by regional authorities. Consistent with this conjecture, a recent survey finds that about one-third of the surveyed U.S. universities assessed regional development objectives as highly important to their technology transfer strategies. These universities were predominantly public (Belenzon and Schankerman, 2009).

In summary, the above considerations and the available prior evidence from various contexts lead us to expect that regional firm populations and private-sector innovation co-evolve with related public research activities in the respective region. In the remainder of this paper, we will explore this conjecture in the context of laser research and laser manufacturing in Germany.

3. Industry-science interaction in the evolution of the German laser industry: Historical evidence and descriptive patterns

Lasers are spatially and temporally coherent light sources based on stimulated emission of photons. The range of their potential applications is virtually unbounded, a fact widely appreciated as soon as the first workable laser was demonstrated in 1960. However, laser sources and auxiliary equipment tend to be highly application-specific, and adapting lasers to new applications turned out to be a major obstacle in their diffusion and commercial application. To date, new advances in laser technology have continued to open up new fields of use for which previously available laser sources were not suitable or commercially viable.

Even though the laser is a U.S. invention, German university researchers and pioneering firms such as Siemens and Zeiss engaged in laser research activities right after they learned about the successful operation of the first U.S. lasers (cf. Albrecht, 1997). Numbers of laser-related publications grew rapidly over the first two decades of laser research (Albrecht et al., 2011). From the beginning, German funding organizations and policy makers were ready to support the fledgling technology. In the 1960s and 1970s, priority programs of the *Deutsche Forschungsgemeinschaft* (DFG) helped establish laser research at universities. These activities also supported the education of early German laser experts. Promotion of more application-oriented laser research started after the Federal Ministry for Research and Technology (*Bundesministerium für Forschung und Technologie*; BMFT) was established in 1968. The new ministry immediately began to fund laser-related projects, and the number of newly commissioned projects took off in the mid-1980s (Fabian, 2012). The BMFT's first research program dedicated to lasers was introduced in 1987. It specifically called for collaborative research projects by industrial and public research partners. Behind this program, as well its successor programs, "Laser 2000" (1993) and "Optical Technologies" (2002), was the ministry's conviction that the German laser industry severely lagged behind its international competitors. These programs also reflect the ministry's activist stance with regard to innovation and industrial policy.

Backed by the ministry, the major German laser producers organized a formalized network called *Arbeitskreis Lasertechnik* in 1984. The *Arbeitskreis* right away began to lobby for the subsidization of industrial laser research as well as the new establishment of application-oriented public research centers. These lobbying efforts fell on open ears in the ministry, as they helped legitimize its activist aspirations and efforts. Incumbent laser firms also played an active role in location choices of new research centers, most importantly the Fraunhofer Institute for Laser Technology (ILT), which eventually was established in Aachen in 1985. The location of this institute was fiercely contested among the regional governments of three *Bundesländer* (cf. Fabian, 2012). Northrhine-Westfalia supported Aachen, Baden-Wuerttemberg fought for its own capital, Stuttgart, and Berlin was likewise backed by its regional government. Industrial interests were actively involved in the fight. Most notable in this context is the head of Stuttgart-based Trumpf Laser, Berthold Leibinger, then a board member of the Fraunhofer Society as well as an R&D policy advisor for the government of Baden-Wuerttemberg. As part of his efforts to locate the new institute close to his own firm, Leibinger even attempted to overturn the Fraunhofer Society's decision in favor of Aachen (ibid.).

Fraunhofer's eventual choice of Aachen did not prevent the losing regions from founding their own laser research centers focusing on applications in materials processing. The *Institut für Strahlwerkzeuge* (IfSW) in Stuttgart, the *Festkörper-Laser-Institut* (FLI) in Berlin, and the *Laserzentrum Hannover* were all established in 1986/1987. Again, the establisment of these institutes was accompanied by substantial industry lobbying. For instance, Trumpf's Leibinger helped shape the agenda of the IfSW and was actively involved in the decision about who should be leading it (ibid.). In other cases such as the FLI, laser producers became cosponsors of the newly established institutes. These events illustrate how laser firms influenced high-level policy decisions on laser-related public research.

Patent and publication data can be used to obtain more micro-level evidence of university-industry interaction at the level of individual research groups. To the extent that inventors from public research show up in patents, this documents their involvement in (early stages of) innovation activities. However, it is not easy to actually measure the role of university researchers in patenting, because individual inventor affiliations are not recorded in patent data, and the majority of patents covering inventions by university researchers are not applied for by universities. In the German case, identifying university-invented patents is particularly difficult for the pre-2002 years when university inventors retained the intellectual property rights in their inventions (the "professors' privilege"). Albrecht et al. (2011) identified university inventors in German laser-related patent applications by matching inventor names with a list of university professors in relevant disciplines. This matching resulted in 391 patent applications (co-) invented by university professors; a share of about 11.9% of all 3273 patent applications in IPC subclass H01S recorded for the time period 1960–2005. However, of the 349 applications only 91 (or about 2.8% of all H01S applications) had an active producer of laser sources among their applicants (based on the laser firm dataset underlying the analysis in Buenstorf, 2007). Only in these 91 cases do the patent data provide evidence of direct involvement of public research in the innovation activities of German laser source producers. An additional number of 71 patents were applied for by other firms. The remainder has universities, other public research organizations or individuals as applicants. Inventor and applicant addresses indicate that about half of all the firm patents listing university inventors are based on local collaboration.

Laser-related scientific publications were analyzed by Fritsch and Medrano Echalar (2015) as well as in Buenstorf et al. (2015). They were obtained from two main sources. For the 1960–1970 period we employ the *Physikalische Berichte*, an annual register of relevant international and German scientific publications. Our publication measure for later years is based on the INSPEC database. Laser publications were identified by a keyword search for "laser", "lasing" and "lasers" in titles and in abstracts. For the search of early laser publications in the *Physikalische Berichte*, the terms "stimulated photon emission", "microwave frequency doubling in ruby", "parametric amplification and oscillation", and "resonators" were also included in the query. We obtained a total of 32,827 laser-related publications from the time period 1960–2007.

Retrieving author affiliations in publication data is in principle straightforward. However, for the time period under investigation, the INSPEC database only provides a single author affiliation per article (generally, the affiliation of the first author listed). This is unambiguous only in the case of single-authored papers, which account for a minority of articles in laser research. To identify university-industry collaborations, we constructed an indicator of articles co-authored by individuals from different types of organizations by recursively inserting identified author affiliations into other papers co-authored in the same year. To the extent possible, for the years before 1990 we limited the search to publications from West Germany.

There are 6562 publications with two authors. For 1291 of these (19.7%) we were able to match both authors with their affiliations. In the vast majority of cases, both authors have the same affiliation. Where affiliations differ, they tend to be from the same type of organization. This holds both for public research and for firms (including firms that do not produce laser sources themselves). Interestingly, it also holds for public research institutes whose mission is to interact with private-sector firms (such as Fraunhofer Institutes or the IfSW). Among the articles with two authors, we only found 26 instances of co-authorship between public research and industrial R&D (2% of all cases with two identified affiliations). For the 6843 articles with three authors, we were able to retrieve at least two author affiliations in 2179 cases. Again, only 51 of these (2.3%) reflect co-authorships between authors from public research and industrial R&D. Finally, for the remaining 15,172 articles with more than three authors, at least two author affiliations could be identified in 7764 cases. In this group the share of co-authorships between public research and firms reaches 3.8% (295 articles). Identified author affiliations suggest that about 37% of all articles co-published by public research and industrial R&D involve researchers from the same region.

Taken together, patent and publication data thus indicate a modest overall level of direct interaction between public research and industrial R&D, with a substantial share of interaction taking place within the same region[4]. However, besides joint patents and papers, there are other links between public research and private-sector R&D. Prominent among these is the migration of university graduates to corporate R&D laboratories. We can study these "embodied" knowledge flows in more detail by focusing on individuals who obtained doctoral degrees in laser-related research and then became inventors of patents related to laser sources. To do so, we conducted a text search for "laser" in the dissertation database of the *Deutsche Nationalbibliothek*, the national library where universities are required to deposit a copy of all doctoral dissertations. This has the advantage that we can search for laser research across disciplinary boundaries and in a database that consistently covers the entire time period under investigation. Excluding medical research, where lasers are frequently used only as research tools, our data encompass a total of 4845 dissertations from 1960 to 2005 (cf. Buenstorf and Geissler, 2014, for details). We then matched the author names of these dissertations with the laser-related patent applications described above. Laser-educated inventors thus identified account for a substantial share of the German laser patents: their overall share is almost 28%. The vast majority of their patents have firms as applicants, even though these were not always commercial laser source producers. If only the patents of laser source producers are considered, the share of laser-educated inventors is about 21%. Inventor addresses suggest that about 36% of the laser-educated inventors patented in the same region where they obtained their doctoral degree. Buenstorf and Geissler (2014) moreover identified 28 authors of laser-related dissertations among the founders of 143 laser producers that entered in Germany between 1960 and 2003, often locating in the vicinity of the parent university. This suggests a non-negligible role of doctoral training in the breeding of future laser entrepreneurs.

Still closer to our interest in the co-evolutionary dynamics of regional firm populations and public research, we can finally look at how activities in laser-active regions developed over time. In this regard, it is illustrative to compare (West) Berlin and Munich, the two leading regions in both laser-related public research and the number of laser producers. The technical universities of both cities were among the pioneering institutions in public laser research. However, key laser researchers in Berlin are known to have been particularly reluctant about industry contacts (Albrecht, 1997), and the first entry of a laser producer in (West) Berlin is only recorded in 1984. In contrast, Munich had Siemens as an early laser producer, and already in 1975 we observe five laser producers in the Munich region. Did these differences matter for subsequent developments in both regions? One indication they did is that, while the laser research activities of both technical universities developed in a rather similar way (in terms of laser-related dissertations and publications), and the laser firm populations of both cities increased substantially, the number of laser firms has always been larger in Munich than in Berlin. Perhaps even more telling is the development of laser research in the other large university of either region, i.e. Free University in Berlin and *Ludwig-Maximilians-Universität* (LMU) in Munich. Both these universities have developed into substantial hubs of laser research, but LMU has consistently been characterized by a much larger output of laser-related work (e.g., a total of 193 laser-related dissertations from 1960–2007 versus only 89 at Free University in Berlin).

Broadening the focus to other regions with important technical universities, we find similar differences indicating that university research has been influenced by private-sector laser activities. For instance, in the German Southwest both Karlsruhe and Stuttgart are prominent early centers of laser-related public research (Albrecht, 1997). However, in Stuttgart, home to industry leader Trumpf which actively tried to shape its research environment (see above), university laser research increased much stronger over time than it did in Karlsruhe, which lacked an important player in the industry (overall, 270 versus 127 laser-related dissertations). A similar patterns emerges from comparing Braunschweig to Göttingen, two major universities located in comparable Northern cities. The Braunschweig region has never been home to a major laser producer, and even though its university is one of Germany's leading technical universities, with a total of 72 dissertations university laser research has remained of modest scale. In contrast, Göttingen, equipped with a less technology-oriented university but a major laser producer (Lambda Physik, later part of global market leader Coherent) as well as an established tradition in the optical industry, has grown into an important center of university laser research (145 laser-related dissertations in total).

These patterns obviously cannot prove the importance of co-evolutionary dynamics of regional firm populations and public

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[4] Given the limitations of our data and approach, these numbers can only been considered a rough, lower bound estimate of scientific articles co-authored by individuals from different (types of) organizations. Moreover, we have no information about how exactly these co-authorships have come about. We suspect that a substantial share of the noted co-authorships across organizations is based on job mobility of individual authors, reflecting articles that were written when the authors still had the same affiliation.

research. They nonetheless suggest that this co-evolution is real and that it may lead to sizeable differences in the long-time development of the individual regions. In the next section, we will further explore this issue based on an econometric analysis.

4. Regional co-evolution of firm population, innovation and public research: An exploratory econometric analysis

In the previous section we presented qualitative evidence and quantitative indicators suggesting a substantial degree of interaction and the interdependence of firms, private-sector R&D and public research in the evolution of German laser research and manufacturing. In this section we begin to trace these co-evolutionary dynamics econometrically. Building on earlier research that demonstrates the importance of regional university research for firm entry into the German laser industry (Buenstorf and Geissler, 2011; Buenstorf et al., 2015), we estimate reduced-form vector autoregressive (VAR) models allowing for mutual interdependence between regional laser firm populations, private-sector R&D (as evidenced by patent data), as well as public research (as evidenced by dissertations or publications). The analysis is based on annual data covering the time period between the inception of laser research in 1960 and the mid-2000s. It is restricted to West(ern) Germany and Berlin because the innovation system of pre-1990 socialist East Germany dramatically differed from the Western one and meaningful dynamics of the firm population cannot be identified for the centrally planned socialist economy.

4.1. Data

Information about the relevant firm population of laser source producers is taken from Buenstorf (2007). As our proxy of laser-related R&D we use the population of IPC H01S patent applications with German applicants at the German Patent Office from 1960 to 2005 (a total of 3297 patents; cf. Section 3 above). Patents of universities and non-university public research organizations are excluded from the analysis, which provides us with a measure of private-sector R&D activities. Recall that the scope of these activities goes beyond the narrowly defined laser industry (and thus our population of laser firms). Many of the relevant patents were applied for by manufacturing firms that were no commercial producers of laser sources. This is consistent with the nature of the laser as a general purpose technology utilized in a broad range of industrial applications.

We employ two alternative indicators of public research. Laser-related scientific publications provide the primary indicator. The publication data used in the analysis corresponds to the one described in the previous section. Publications by authors with private-sector affiliations (which account for only a small share of the overall publication output) were eliminated. Alternatively, public research activities are measured by laser-related doctoral dissertations. Advising doctoral dissertations constitutes a strong signal that a university researcher is interested in a particular field of research. We employ the laser dissertation dataset from Buenstorf and Geissler (2014) introduced above.

Annual observations for all variables are aggregated to the geographic level of planning regions (*Raumordnungsregionen* or ROR). Planning regions aggregate several districts (*Landkreise*; NUTS3) such that commuter flows across regional boundaries are minimized, but are more fine-grained than the NUTS2 regions defined by the European Union. Germany currently has 96 planning regions. As the delineation of planning regions proceeds along administrative boundaries, planning regions provide a good balance of data availability and adequacy as functional geographic units. They are widely used as geographic units in empirical research on Germany (e.g., by Fritsch and Medrano Echalar, 2015). As a robustness check, the analysis is repeated at the broader level of *Bundesländer* (NUTS1).

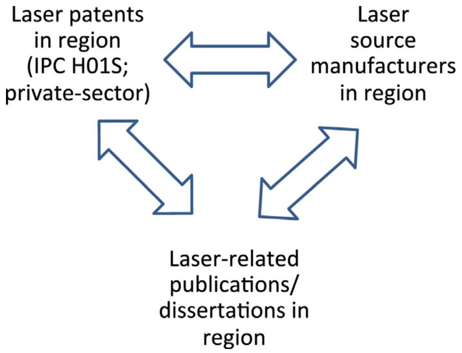

Fig. 1. Empirical model of regional co-evolutionary dynamics in German laser research and laser manufacturing (see Section 4.2 for explanation).

We include in the analysis all West German planning regions with universities whose researchers were “at risk” of performing laser research in any given year. We constructed this risk set by first identifying the population of universities from an official directory published by the German Rectors' Conference (*Hochschulrektorenkonferenz*). To identify laser-relevant departments, we then used information from the *Vademecum Deutscher Lehr und Forschungsstätten* (1957, 1961, 1964, 1968) published by the *Stifterverband für die Deutsche Wissenschaft*, as well as from annual official study guides (*Studien- und Berufswahlführer*). Summary statistics for the main variables and pair-wise correlations are reported in Tables 1 and 2.

4.2. Vector autoregressions

To analyze statistical associations between regional measures of firm population size, private-sector R&D and public research, we estimate a series of reduced-form panel vector autoregression (VAR) models (Sims, 1980). VAR models are well-established to study relationships between macroeconomic time series. They have also been applied to issues of industrial dynamics (cf., e.g., Coad and Broekel, 2012). In a reduced-form VAR model, variables are regressed on their own lagged values as well as lagged values of all other relevant variables. Each individual regression is estimated via OLS. The reduced-form VAR models estimated in this study can be expressed as:

$$Z_{i,t} = a + \sum_{\tau=t-s}^{t-1} b_{i,\tau} Z_{i,\tau} + \varepsilon_{i,t} \tag{1}$$

where Z is a vector including our measures of public research activities (alternatively measured by publication or dissertation counts), private-sector patent applications and the size of the regional population of laser source producers (cf. also the graphical representation of the model in Fig. 1). Publication and dissertation data were aggregated for all universities located in the same planning region (ROR) i, and the analysis is based on annual observations ($1960 \leq t \leq 2003$). We assume that research projects leading to publications or patents have a duration of three years. For dissertation projects we assume a five-year duration. State variables of the number of ongoing publication, patent and dissertation projects were constructed from the observable outcomes using these assumptions. This procedure provides us with an unbalanced panel data

Table 1
Summary statistics and correlations of the main variables (1960–2004).

	Descriptives					Correlations		
Variable	Obs	Mean	Std. dev	Min.	Max.	Producers	Patents	Publications
Producers	1621	0.5632326	1.52039	0	16	1.0000		
Patents	1621	4.046309	11.83098	0	119	0.5039	1.0000	
Publications	1621	19.25108	52.66299	0	525	0.7345	0.3767	1.0000
Dissertations	1621	10.21098	16.05161	0	111	0.6411	0.3632	0.6488

Table 2
Summary statistics and correlations of the main variables (first differences, 1960–2004).

	Descriptives					Correlations		
Variable	Obs	Mean	Std. dev	Min.	Max.	ΔProducers	ΔPatents	ΔPublications
ΔProducers	1579	0	0.5860655	−13	3	1.0000		
ΔPatents	1579	0.0877137	2.642794	−34.5	22.5	0.0300	1.0000	
ΔPublications	1579	0.9689677	7.101539	−70	125	0.2331	0.1728	1.0000
ΔDissertations	1579	0.4224193	2.966143	−19	28	0.1061	0.0373	0.1924

set with annual observations capturing the time period from 1960 to 2004[5].

Non-stationarity (i.e., time-varying expected values and variances) is a basic concern in analyzing statistical associations between time series, as it may induce spurious correlation. Fisher-type tests did not reject the Null hypothesis of non-stationarity (unit roots) in the original time series. In contrast, the Null hypothesis of non-stationarity in all panels was rejected for the first-differenced time series. Accordingly, all estimations are performed in first differences, which also allows us to control for time-invariant unobserved heterogeneity[6].

A crucial limitation of the reduced-form panel VAR approach is that estimates only show correlations, and not causal relationships, between the interdependent variables included in Z. Moreover, given that they do not reflect the interdependence among the contemporaneous variables, the estimates of individual coefficients in the 3×3-matrix b have no direct economic interpretation. Not even their sign can be interpreted in a straightforward way (Hoover, 2001). However, we can use the reduced-form VAR models to test for Granger causality between variables (Granger, 1969; Stock and Watson, 2001)[7]. It is the results of these Granger causality tests that our subsequent discussion focuses upon. We do not have strong theoretical priors about the number of lags s to be included in the VAR models, but generally expect the relevant interdependencies to be between variables of relatively short lags. The results of Granger causality tests are therefore reported for models with up to five lags ($s \leq 5$). *P*-values of these tests are shown in Table 3.

Adopting publications as the proxy of public research, Table 3 shows that irrespective of lag length, both changes in the number of patents and changes in the number of publications significantly predict subsequent changes in the number of regional laser producers (left panel, first column). We likewise find that patents are Granger-caused by the size of the regional laser firm population as well as by publications (left panel, second column). Except for the producer variable in the model with three lags, the Null of no Granger causality is always rejected at the .05 or the .01 level. Consistent with prior work, these findings suggest a systematic effect of public research on private-sector activities, as well as a mutual interdependence of firm population size and private-sector R&D. Results of tests for Granger causality running from private-sector activities (firm population size, number of laser-related patents) on the public research activities in the same region are reported in the third column of the left panel. Again, we find strong evidence of Granger causality for all considered lag lengths. Taken together, these findings are consistent with systematic co-evolution of firm population size, private-sector R&D and public research at the regional level. The developments in individual regions discussed at the end of the previous section thus appear to be indicative of the more general dynamics of German laser research and laser manufacturing since 1960.

Granger causality tests using regional dissertation counts as an alternative proxy of public research activities yield similar, but generally slightly less clear-cut results (Table 3, right panel). Again, patent counts consistently Granger-cause regional firm population sizes and vice versa (except for the model with three lags). In contrast, public research does not predict subsequent private-sector activities in the models with smaller numbers of lags. Interestingly, though, the above finding that public research is Granger caused by the number of laser firms and private-sector patents in the same region is reproduced for this alternative measure of public research activities.

4.3. *Robustness checks*

We assess the robustness of the above findings using four different approaches. First, the reduced-form VARs are re-estimated for shorter time periods. Second, we repeat the analysis for the broader geographic level of *Bundesländer*. Third, the assumed duration of dissertation projects is varied. Fourth, we estimate the hazard of university departments to newly enter laser-related research.

Splitting the time period under investigation in half and re-estimating the reduced-form VARs for the years 1960–1982 (Table 4) and 1983–2003 (Table 5) yields similar results to those obtained for the full sample. If anything, results for the split sample indicate that co-evolutionary relationships between private and public-sector activities may have become stronger over time. Using the publication-based measure of public research (left panel of Table 4), 21 of the 30 Granger causality tests for the earlier time period are significant at the .05 level or better (25 are significant at least at the 0.10 level). The corresponding numbers for the models with the dissertation-based measure (right panel of Table 4) are 16 and 19. In the 1983–2002 time period, 26 of the 30 Granger causal-

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[5] Our raw data generally extend to 2007, but final years are lost due to our transformation of dissertation, publication and patent data into measures of ongoing projects.

[6] We alternatively used regional percentages of the annual totals for all variables, for which the Null of unit roots in all panels also was rejected. Results were similar to those reported below and are available upon request.

[7] The concept of Granger causality is based on testing whether lagged values of variable X improve the prediction of another variable Y. Variable X Granger causes variable Y if an F-test of joint significance of all included lags of X is significant in a model of Y. Granger causality may be uni- or bidirectional.

Table 3
Results of Granger causality tests (ROR level; five-year dissertation duration) (first differences; 1960-2003).

	(*p*-Values)	ΔProducers	ΔPatents	ΔPublications	ΔProducers	ΔPatents	ΔDissertations
L1	ΔProducers	x	0.0218	0.0000	x	0.0108	0.0001
	ΔPatents	0.0033	x	0.7808	0.0452	x	0.1627
	ΔPub/Δdiss	0.0000	0.0233	x	0.4902	0.5369	x
L2	ΔProducers	x	0.0060	0.0000	x	0.0029	0.0007
	ΔPatents	0.0000	x	0.0000	0.0001	x	0.0081
	ΔPub/Δdiss	0.0000	0.0057	x	0.3105	0.6742	x
L3	ΔProducers	x	0.2238	0.0000	x	0.1887	0.0012
	ΔPatents	0.0000	x	0.0000	0.0000	x	0.0134
	ΔPub/Δdiss	0.0000	0.0001	x	0.2777	0.3662	x
L4	ΔProducers	x	0.0038	0.0000	x	0.0002	0.0000
	ΔPatents	0.0000	x	0.0000	0.0000	x	0.0024
	ΔPub/Δdiss	0.0000	0.0003	x	0.3299	0.0004	x
L5	ΔProducers	x	0.0007	0.0000	x	0.0000	0.0000
	ΔPatents	0.0000	x	0.0000	0.0000	x	0.0448
	ΔPub/Δdiss	0.0000	0.0032	x	0.0005	0.0016	x

Note: L1–L5 denote the number of lags *s* included in the model.

Table 4
Results of Granger causality tests (ROR level; five-year dissertation duration) (first differences, 1960–1982).

	p-Values	ΔProducers	ΔPatents	ΔPublications	ΔProducers	ΔPatents	ΔDissertations
L1	ΔProducers	x	0.0299	0.2097	x	0.0671	0.0276
	ΔPatents	0.0000	x	0.1483	0.0000	x	0.0467
	ΔPub/Δdiss	0.0348	0.0974	x	0.4596	0.5713	x
L2	ΔProducers	X	0.0444	0.0186	x	0.1885	0.0745
	ΔPatents	0.0000	x	0.0023	0.0000	x	0.4973
	ΔPub/Δdiss	0.0506	0.0806	x	0.4524	0.0390	x
L3	ΔProducers	X	0.5963	0.0107	x	0.9669	0.0218
	ΔPatents	0.0000	x	0.0000	0.0000	X	0.2136
	ΔPub/Δdiss	0.0145	0.0008	x	0.6598	0.0060	x
L4	ΔProducers	X	0.3682	0.1030	x	0.3836	0.0303
	ΔPatents	0.0000	x	0.0003	0.0000	X	0.0256
	ΔPub/Δdiss	0.0089	0.0289	x	0.5696	0.0000	x
L5	ΔProducers	x	0.0006	0.0960	x	0.0006	0.0005
	ΔPatents	0.0000	x	0.0000	0.0000	x	0.0855
	ΔPub/Δdiss	0.0022	0.0497	x	0.4845	0.0000	x

Note: L1–L5 denote the number of lags *s* included in the model.

Table 5
Results of Granger causality tests (ROR level; five-year dissertation duration) (first differences, 1983–2003).

	p-Values	ΔProducers	ΔPatents	ΔPublications	ΔProducers	ΔPatents	ΔDissertations
L1	ΔProducers	x	0.0335	0.0000	x	0.0184	0.0021
	ΔPatents	0.6747	x	0.3928	0.7006	x	0.2131
	ΔPub/Δdiss	0.0000	0.0006	x	0.7158	0.6610	x
L2	ΔProducers	x	0.0329	0.0000	x	0.0172	0.0140
	ΔPatents	0.0836	x	0.0002	0.0915	x	0.0057
	ΔPub/Δdiss	0.0000	0.0025	x	0.3667	0.2560	x
L3	ΔProducers	x	0.3607	0.0000	x	0.1500	0.0033
	ΔPatents	0.0000	x	0.0001	0.0000	x	0.0005
	ΔPpub/Δdiss	0.0000	0.0001	x	0.3827	0.1815	x
L4	ΔProducers	x	0.0027	0.0000	x	0.0001	0.0000
	ΔPatents	0.0000	x	0.0000	0.0000	x	0.0004
	ΔPub/Δdiss	0.0000	0.0000	x	0.4926	0.0033	x
L5	ΔProducers	x	0.0000	0.0000	x	0.0000	0.0002
	ΔPatents	0.0000	x	0.0001	0.0000	x	0.0068
	ΔPub/Δdiss	0.0000	0.0003	x	0.0027	0.0136	x

Note: L1–L5 denote the number of lags *s* included in the model.

ity tests are significant at the .05 level or better in the models using the publication measure of public research (left panel of Table 5). The same holds for 19 of the 30 tests using the dissertation measure (right panel of Table 5).

Results for reduced-form panel VARs at the level of the 11 Western *Bundesländer* are reported in Table 6. In line with the prior results, we find that changes in the number of publications are Granger-caused by the numbers of regional producers and patents. This resonates with the historical evidence that laser firms lobbied regional policy makers in support of public laser research. Using the publication proxy, the results also suggest an effect of public research on the laser firm population size, as well as an effect of laser producers on private-sector R&D. Not surprisingly given the smaller number of observations, results at the *Bundesländer* level

Table 6
Results of Granger causality tests (Bundesländer level; five-year dissertation duration) (first differences; 1960–2004).

	p-Values	ΔProducers	ΔPatents	ΔPublications	ΔProducers	ΔPatents	ΔDissertations
L1	ΔProducers	x	0.0172	0.0000	x	0.0157	0.0000
	ΔPatents	0.7624	x	0.7426	0.9909	x	0.1503
	ΔPub/Δdiss	0.0859	0.2541	x	0.1734	0.2957	x
L2	ΔProducers	x	0.0027	0.0000	x	0.0030	0.0000
	ΔPatents	0.1035	x	0.0038	0.0382	x	0.0745
	ΔPub/Δdiss	0.0394	0.2847	x	0.0541	0.3782	x
L3	ΔProducers	x	0.0120	0.0000	x	0.0179	0.0000
	ΔPatents	0.0016	x	0.0059	0.0082	x	0.0969
	ΔPub/Δdiss	0.0000	0.2274	x	0.1719	0.0605	x
L4	ΔProducers	x	0.0026	0.0004	x	0.0028	0.0000
	ΔPatents	0.0062	x	0.0456	0.0208	x	0.0868
	ΔPub/Δdiss	0.0000	0.2614	x	0.0967	0.1166	x
L5	ΔProducers	x	0.0056	0.0006	x	0.0034	0.0000
	ΔPatents	0.0274	x	0.0044	0.1112	x	0.0584
	ΔPub/Δdiss	0.0000	0.4152	x	0.0000	0.2581	x

Note: L1–L5 denote the number of lags *s* included in the model.

are generally less strongly significant. Similar to the level of planning regions, findings obtained with the publication proxy of public research are more clear-cut than those using the dissertation proxy.

We next probe into the assumed duration of dissertation projects, a potentially critical assumption in the above analysis. To this purpose, we re-estimate the VAR models, now assuming a shorter four-year duration of dissertation projects. Results of these re-estimations are reported in Table 7. Due to the shorter assumed duration of dissertation projects, we can now extend the analysis to the year 2004, which explains the changes in the results of the models using publications as a proxy of public research activity. Most notably, patents do not significantly Granger-cause changes in regional firm population sizes in these models (Table 7, left panel). For the alternative proxy of dissertation projects, we consistently find significant Granger-causal relationships running from public research to the regional firm population size (Table 7, right panel). In contrast, the evidence for reverse Granger causality running from firm population size to public research is considerably weaker than in the original estimates, pointing to potential issues of measurement error. This is not very surprising given the admittedly crude proxies available to our analysis, which covers the complete West German laser industry for more than 40 years starting at the outset of the industry. Irrespective of the concrete model specification, however, we consistently obtain evidence suggestive of co-evolutionary processes, as there are significant Granger-causal relationships from public research to private-sector activities as well as in the opposite direction.

The final robustness check focuses on the impact of regional private-sector activities on public research, which is a key element of the proposed co-evolutionary dynamics, using a different statistical methodology. Specifically, we estimate semi-parametric Cox regressions to trace whether the hazard of university departments to newly enter into laser research is associated with the regional presence of laser producers. The main limitation of this approach is that the number of laser producers in a region is assumed to be exogenous. The results of the hazard models can therefore only be taken as suggestive.

To estimate the hazard models, we first developed a risk set of universities whose researchers could in principle have started laser-related research activities. Using the same data sources as in the above analysis, we identified all departments in physics and chemistry, as well as mechanical and electrical engineering departments, and when they were established. The former are aggregated into synthetic "science" departments, and the latter are likewise aggregated into "engineering" departments. These synthetic departments constitute the risk set for the hazard analysis. A total of 55 West German (including West Berlin) universities with laser-relevant "science" departments (52 departments in total) or "engineering" departments (32 in total) is thus identified. Given the drastic expansion of the West German system of higher education beginning in the 1970s, many universities enter the risk set after 1960. For pre-existing departments, the time at risk begins in 1960 (when the laser was invented). Departments are assumed to enter laser research in the first year in which three or more ongoing laser-related dissertations are recorded[8]. All estimations are based on annual observations and allow covariate values to vary over time. Standard errors are clustered by university.

Results of the hazard models are presented in Table 8. Our baseline specification (Model 1 in Table 8) shows that the hazard of entry into laser research is significantly higher for universities located in regions with larger populations of laser producers. In Model 2, we estimate separate coefficients for the association of the laser producer variable with departments of traditional universities (*Uni*), respectively technical universities (*TU*). Both coefficients are positive and significant. In Model 3, the number of regional laser patents is added to the specification of Model 1. No significant association with the hazard rate is found, and the coefficient estimate for the presence of laser producers changes little[9]. Finally, in Model 4, we further include an indicator denoting engineering departments and also control for (log) population density of the university region. These changes dampen the coefficient estimate of the producer variable, which however remains sizeable and marginally significant at the .10 level.

5. Concluding remarks

In this paper, we took the idea that industries co-evolve with their institutional environment (which dates back to Nelson, 1994) as a starting point of a detailed analysis of regional interdependencies between firm population sizes, private-sector R&D and public research. We did so in the empirical context of laser research and laser manufacturing in (West) Germany, which has attracted substantial prior attention by historians as well as economists. Based

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[8] Very similar results were obtained when we alternatively assumed entry in the year of the department's first laser-related dissertation.

[9] Both variables are correlated. The patent variable is significant if the producer variable is dropped from the specification.

Table 7
Results of Granger causality tests (ROR level; four-year dissertation duration) (first differences; 1960-2004).

	(*p*-Values)	ΔProducers	ΔPatents	ΔPublications	ΔProducers	ΔPatents	ΔDissertations
L1	ΔProducers	x	0.0263	0.0000	x	0.0139	0.2016
	ΔPatents	0.1149	x	0.3552	0.0137	x	0.0132
	ΔPub/Δdiss	0.0000	0.0150	x	0.0000	0.5880	x
L2	ΔProducers	x	0.0090	0.0000	x	0.0034	0.3017
	ΔPatents	0.1525	x	0.0004	0.0298	x	0.0557
	ΔPub/Δdiss	0.0000	0.0034	x	0.0000	0.0300	x
L3	ΔProducers	x	0.1969	0.0000	x	0.1473	0.0350
	ΔPatents	0.2413	x	0.0000	0.0838	x	0.0283
	ΔPub/Δdiss	0.0000	0.0000	x	0.0000	0.1820	x
L4	ΔProducers	x	0.0029	0.0000	x	0.0004	0.0884
	ΔPatents	0.3490	x	0.0000	0.1327	x	0.0078
	ΔPub/Δdiss	0.0000	0.0002	x	0.0000	0.0824	x
L5	ΔProducers	x	0.0001	0.0000	x	0.0000	0.2997
	ΔPatents	0.4325	x	0.0000	0.2333	x	0.0007
	ΔPub/Δdiss	0.0000	0.0019	x	0.0000	0.1047	x

Note: L1–L5 denote the number of lags *s* included in the model.

Table 8
Results: hazard of departmental entry into laser research (1960-2004).

	Model 1	Model 2	Model 3	Model 4
Laser producers	0.3859*** (0.1134)		0.3434** (0.1389)	0.2630* (0.1505)
TU*laser producers		0.2950*** (0.0601)		
Uni*laser producers		0.5647** (0.2278)		
Laser patents			0.0174 (0.0343)	0.0201 (0.0355)
Engineering department				−0.2268 (0.2839)
Pop. density (log)				0.3970** (0.1778)
Observations (subjects)	2119 (84)	2119 (84)	2119 (84)	2119 (84)
Log-likelihhod	−186.6462	−185.7728	−186.4901	−183.8072
$p < \text{chi}^2$	0.0007	0.0000	0.0031	0.0010

Standard errors (clustered by university) in parentheses.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

on qualitative information as well as reduced-form panel vector autoregressions covering a time span of more than 40 years, we not only found that private-sector activities seem to benefit from the activities of co-located universities and non-university public research organizations, as a sizeable prior literature suggests. Our findings also indicate that public research is responsive to the regional presence of innovative firms. These mutually reinforcing relationships between public research and private-sector activities are consistent with the notion of co-evolution. They resonate with the work of historians of science who have long insisted that advances in science are not independent from technological development. They also suggest that the co-evolutionary dynamics that Murmann (2003, 2013a,b) identified in the context of the historical synthetic dye industry also characterize contemporary high-tech environments.

Our study differs from these prior contributions in its level of analysis as well as in its empirical approach. On the one hand, our findings show that the influence of industrial R&D and technological development on the progress of science is not limited to the fundamental interdependencies that historians of science have focused upon, but can also be traced at the more mundane level of regional interaction. On the other hand, we have used micro-level panel data on various populations of relevant actors (firms, universities, patents, publications, doctoral dissertations etc.) covering an extended period of laser research and manufacturing from its inception in 1960. This approach is informed by the empirical work on industry evolution (e.g., Gort and Klepper, 1982; Klepper, 1996; Agarwal et al., 2004). We are convinced that it is equally useful to study the evolution of innovation systems and may thus help to overcome some of the limitations in the empirical work on innovation systems that have been criticized by Fagerberg (2003) and others. At the same time, our findings put into perspective the large number of empirical studies that exclusively focus on the regional impact of public research activities without considering potential effects from the private sector on public research.

This study can only be an exploratory first attempt to probe into these issues. While it benefits from substantial prior research on the same empirical context, it is nonetheless constrained by data availability. We therefore cannot rule out that our results are biased by measurement error and omitted variable bias. In addition, we were limited in our ability to identify causal effects. Neither a plausible quasi-experimental situation nor a suitable design for instrumenting relationships could be exploited. The adopted reduced-form vector autoregressions are an imperfect substitute, as they only allow us to detect Granger-causal relationships between pairs of variables. In spite of these limitations, our results provide systematic empirical evidence that, in line with the notion of co-evolution, regional interdependencies between public research and related private-sector activities run both ways. The development of regional firm populations benefits from the activities of co-located universities and other public research facilities, and public research likewise benefits from the regional presence of commercial firms in related industries. As is indicated by the development of some leading German university regions, the impact of these benefits may be substantial.

Our findings attest to the importance of adopting a systemic perspective in innovation policy. They strengthen the rationale of regional collaboration and networking policies that cut across the public–private divide. From the perspective of firms' innovation management, our analysis indicates that fostering ties to local universities is a worthwhile activity. As can be seen from the historical evidence on the German laser industry, the firm does not need to take its research environment as given, but may actively try to shape it to its own benefit. From the perspective of universities and public research organizations, we find that engagement with the private sector is not only an increasingly emphasized task, but may also yield substantial benefit for public research. While these conclusions are based on data for a single national industry, we have no reason to believe that it is limited to the laser industry and/or Germany, but would expect to find similar dynamics in other high-tech industries and other countries.

In concluding, we note that our findings also raise important new questions. What are the conduits of the interdependencies suggested by the data, and how do they evolve over time? What causes underlie the observable differences between publications and dissertations as measures of public research activity? How and to what extent are the relationships between public research and private-sector firms mediated by public policy? To what extent can we observe similar co-evolutionary dynamics also within the public or private-sector activities, e.g., between different disciplines involved in the same field of research, or between different stages of an industrial value chain? How is our finding that co-evolutionary dynamics appear to have become more important over time related to structural specificities of the laser such as the absence of a shakeout in the number of active firms for more than four decades (Buenstorf, 2007)? And how would these dynamics be affected if a shakeout were eventually setting in, as has been the case in the U.S. laser industry (Bhaskarabhatla and Klepper, 2014)? By digging even deeper into the empirical material, including the collection of other types of data as well as the integration of complementary methods such as the analysis of innovation networks, future research will hopefully be able to answer these and related questions.

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References

Agarwal, R., Echambadi, R., Franco, A.M., Sarkar, M.B., 2004. Knowledge transfer through inheritance: spin-out generation, development and survival. Acad. Manage. J. 47, 501–522.

Agrawal, A., 2006. Engaging the inventor: exploring licensing strategies for university inventions and the role of latent knowledge. Strateg. Manage. J. 27, 63–79.

Albrecht, H., 1997. Laserforschung in Deutschland 1960–1970. University of Stuttgart (Unpublished Habilitation Thesis).

Albrecht, H., Buenstorf, G., Fritsch, M., 2011. System? What System? The (Co-) Evolution of Laser Research and Laser Innovation in Germany Since 1960. Mimeo University of Kassel.

Audretsch, D.B., Lehmann, E.E., Warning, S., 2005. University spillovers and new firm location. Res. Policy 34 (7), 1113–1122.

Azoulay, P., Ding, W., Stuart, T., 2009. The impact of academic patenting on the rate, quality and direction of (Public) research output. J. Ind. Econ. 57, 637–676.

Belenzon, S., Schankerman, M., 2009. University knowledge transfer: private ownership, incentives and local development objectives. J. Law Econ. 52, 111–144.

Bhaskarabhatla, A., Klepper, S., 2014. Latent submarket dynamics and industry evolution: lessons from the US laser industry. Ind. Corp. Change 23 (6), 1381–1415.

Breschi, S., Lissoni, F., Montobbio, F., 2008. University patenting and scientific productivity: a quantitative study of Italian academic inventors. Eur. Manage. Rev. 5, 91–109.

Buenstorf, G., 2007. Evolution on the shoulders of giants: entrepreneurship and firm survival in the German laser industry. Rev. Ind. Organiz. 20, 179–2002.

Buenstorf, G., Geissler, M., 2011. The origins of entrants and the geography of the German laser industry. Pap. Reg. Sci. 90, 251–270.

Buenstorf, G., Geissler, M., 2014. Like Doktorvater, Like son? Tracing role model learning in the evolution of German laser research. Jahrbücher für Nationalökonomie und Statistik 234, 158–184.

Buenstorf, G., Fritsch, M., Medrano, L.F., 2015. Regional knowledge, organizational capabilities and the emergence of an industry: laser systems production in West Germany, 1975–2005. Reg. Stud. 49 (1), 59–75.

Bush, V., 1945. Science—the endless frontier. In: A Report to the President on a Program for Postwar Scientific Research. U.S. Government Printing Office, Washington, DC.

Castellacci, F., 2007. Evolutionary and new growth theories: are they converging? J. Econ. Surv. 21, 585–627.

Coad, A., Broekel, T., 2012. Firm growth and productivity growth: evidence from a panel VAR. Appl. Econ. 44 (10), 1251–1269.

Cohen, W.M., Nelson, R.R., Walsh, J.P., 2002. Links and impacts: the influence of public research on industrial R&D. Manage. Sci. 48, 1–23.

Cooke, P., Heidenreich, M., Braczyk, H.-J. (Eds.), 2004. Regional Innovation Systems: The Role of Governance in a Globalized World. , second ed. Routledge, London.

Fabian, C., 2012. Technologieentwicklung im Spannungsfeld von Industrie, Wissenschaft und Staat: Zu den Anfängen des Innovationssystems der Materialbearbeitungslaser in der Bundesrepublik Deutschland 1960 bis 1997. Verlag GNT, Diepholz.

Fagerberg, J., 2003. Schumpeter and the revival of evolutionary economics: an appraisal of the literature. J. Evol. Econ. 13, 125–159.

Feldman, M.P., 1994. Knowledge complementarity and innovation. Small Bus. Econ. 6, 363–372.

Fritsch, M., Aamoucke, R., 2013. Regional public research, higher education, and innovative start-ups: an empirical investigation. Small Bus. Econ. 41, 865–885.

Fritsch, M., Medrano Echalar, L.F., 2015. New technology in the region—agglomeration and absorptive capacity effects on laser technology research in West Germany, 1960–2005. Econ. Innovation New Technol. 24 (1–2), 65–94.

Gertner, J., 2012. The Idea Factory: Bell Labs and the Great Age of American Innovation. Penguin Books, New York.

Gort, M., Klepper, S., 1982. Time paths in the diffusion of product innovations. Econ. J. 92 (367), 630–653.

Granger, C.W.J., 1969. Investigating causal relations by econometric models and cross-spectral methods. Econometrica 37 (3), 424–438.

Hicks, D., 1995. Published papers, tacit competencies and corporate management of the public/private character of knowledge. Ind. Corp. Change 4, 401–424.

Hoover, K.D., 2001. Causality in Macroeconomics. Cambridge University Press, Cambridge UK.

Hounshell, D.A., Smith, J.K., 1988. Science and Corporate Strategy: Du Pont R and D, 1902–1980. Cambridge University Press, New York, NY.

Jaffe, A.B., 1989. Real effects of academic research. Am. Econ. Rev. 79, 957–970.

Jaffe, A.B., Trajtenberg, M., 1996. Flows of knowledge from universities and federal laboratories: modeling the flow of patent citations over time and across institutional and geographic boundaries. Proc. Natl. Acad. Sci. 93 (23), 12671–12677.

Klepper, S., 1996. Entry, exit and growth, and innovation over the product life cycle. Am. Econ. Rev. 86, 562–583.

Kline, S.J., Rosenberg, N., 1986. An overview of innovation. In: Landau, R., Rosenberg, N. (Eds.), The Positive Sum Strategy: Harnessing Technology for Economic Growth. National Academy of Engineering, Washington, DC, pp. 275–305.

Leten, B., Landoni, P., van Looy, B., 2014. Science or graduates: how do firms benefit from the proximity of universities? Res. Policy 43 (8), 1398–1412.

Lundvall, B.-A. (Ed.), 1992. National Systems of Innovation and Interactive Learning. New York: Pinter Publishers, London.

Malerba, F., 2002. Sectoral systems of innovation and production. Res. Policy 31 (2), 247–264.

Mansfield, E., 1995. Academic research underlying industrial innovations: sources, characteristics, and financing. Rev. Econ. Stat. 77 (1), 55–65.

Mokyr, J., 2002. The Gifts of Athena: Historical Origins of the Knowledge Economy. Princeton University Press, Princeton, NJ.

Mowery, D.C., Nelson, R.R., Sampat, B.V., Ziedonis, A.A., 2004. Ivory Tower and Industrial Innovation: University-Industry Technology Transfer before and after the Bayh-Dole Act in the United States. Stanford University Press, Stanford CA.

Murmann, J.P., 2003. Knowledge and Competitive Advantage. Cambridge University Press, Cambridge.

Murmann, J.P., 2013a. The coevolution of industries and important features of their environments. Organiz. Sci. 24, 58–78.

Murmann, J.P., 2013b. The co-development of industrial sectors and academic disciplines. Sci. Public Policy 40, 229–246.

Nelson, R.R., 1959. The simple economics of basic scientific research. J. Pol. Econ. 67, 297–306.

Nelson, R.R. (Ed.), 1993. National Innovation Systems—A Comparative Analysis. Oxford University Press, New York, NY.

Nelson, R.R., 1994. The co-evolution of technology, industrial structure, and supporting institutions. Ind. Corp. Change 3, 47–63.
Rosenberg, N., 2004. Science and Technology: Which Way does the Causation Run?, Available at ⟨http://www.crei.cat/activities/sc_conferences/23/papers/rosenberg.pdf⟩ (last accessed November 23, 2014) Paper presented at Stanford University, November 1, 2004.
Sims, C., 1980. Macroeconomics and reality. Econometrica 48, 1–48.
Soete, L., Verspagen, B., ter Weel, B., 2010. Systems of innovation. In: Bronwyn, Hall, Rosenberg, Nathan (Eds.), Handbook of the Economics of Innovation. Elsevier, Amsterdam, pp. 1160–1180.
Stern, S., 2004. Do scientists pay to be scientists? Manage. Sci. 50, 835–853.
Stock, J.H., Watson, M.W., 2001. Vector Autoregressions. J. Econ. Perspect. 15 (4), 101–115.
Stokes, D.E., 1997. Pasteur's Quadrant. Basic Science and Technological Innovation. Brookings, Washington, DC.
Stuart, T., Sorenson, O., 2003. The geography of opportunity: spatial heterogeneity in founding rates and the performance of biotechnology firms. Res. Policy 32, 229–253.