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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 explore the regional co-evolution of firm population size, private-sector patenting and public research in the empirical context of German laser research and manufacturing over more than 40 years from the emergence of the industry to the mid-2000s. Our qualitative as well as quantitative evidence is suggestive of a co-evolutionary process of mutual interdependence rather than a unidirectional effect of public research on private-sector activities.

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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 feedbacks from "later" (i.e., closer to product development) to "earlier" stages. In this paper, we will provide historical and quantitative evidence indicating that these feedbacks are important in the regional co-evolution of industry, innovation, and public research.

A variety of theoretical proposals 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 curiosity-driven basic research can often not be meaningfully distinguished from use-oriented applied research. Prominent contemporary contexts in which the distinction breaks down include solid state physics and biomedical research. At various geographic and sectoral scales, the systems of innovation approach emphasizes the importance of science-industry interaction. This approach played an important role in conceptually discrediting the linear model (Fagerberg, 2003). 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).

A variety of empirical findings support the theoretical contributions pointing to shortcomings of the linear model. Private-sector R&D managers report that public research is equally important to solve 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).

These theoretical and empirical contributions notwithstanding, it is common 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 different empirical contexts. For instance, a substantial number of studies find that public research activities help explain regional rates of innovation (e.g., Feldman, 1994, or Leten et al., 2014) or new firm formation (e.g., Audretsch et al., 2005, or Fritsch and Amoucke. 2014) without addressing potential influences from innovation or entrepreneurship on public research. The same can be said about

[1] The linear model is conventionally attributed to Vannevar 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, which may rather have been a rhetorical device that Bush used to justify sustained public funding of basic research after World War 2.

studies of industry evolution that consider public research as a determinant of regional entry rates (e.g., Stuart and Sorenson, 2003, or Buenstorf and Geissler, 2011).[2]

That the potential impact of private-sector activities on public research is widely neglected in current 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). Adopting the empirical context of the historical synthetic dye industry, Murmann (2003; 2013a; 2013b) has shown how producers in the laggard German industry leveraged their close interaction with university chemists to attain world market leadership.

The prior discussion has mostly focused on the interdependence of science and technological innovation at the aggregate level. In contrast, our principal interest is at 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 easy to find examples suggesting the importance of regional interaction leading 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 August 8, 2014). 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 type 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

[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.

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. If it can be generalized beyond the laser industry, this finding has potentially severe implications for empirical research on science-industry interactions, 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 regional industry affect public research (and vice versa)?

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

Co-evolution has been suggested as a theoretical frame to account for interdependences between industry, technological change, and the institutional environment (Nelson, 1994; Murmann, 2003). The defining characteristic of two (or more) co-evolving populations is that changes in each population have a causal influence on the further evolution of the other(s). The co-evolution concept seems well-suited to complement the systems of innovation approach highlighting the interactive nature of innovation processes. As proponents of the systemic approach (e.g., Lundvall, 1992; Nelson, 1993; Malerba, 2002; Cooke et al., 2004; cf. also Soete et al., 2010, for a survey) have argued, 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. Studying co-evolutionary processes may also help 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.

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. The relevance of reverse causality – technological change driving advances in science – has also been stressed by historians of science (Mokyr, 2002; Rosenberg, 2004). “Technology oriented sciences” (Nelson, 1959) and new fields of engineering often come into existence because already functioning technology is insufficiently well understood. By adding to the understanding of the respective technology, the new fields and disciplines help broaden its "epistemic base" (Mokyr, 2002), which facilitates future improvements of the technology as well as new applications. Researchers in these technology-oriented fields of science and engineering may directly shift the technological frontier or enable those working in private-sector R&D laboratories to do so.

Public research and private-sector innovation are linked through a variety of conduits. Universities educate students and researchers, many of whom subsequently migrate into the private sector and contribute to the human capital stock of incumbent firms. Direct ties between firms and public research 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. Such collaborative and sponsored research helps incumbents advance their technology. In addition, public research may also facilitate new entry into the industry (Nelson, 1994). First, because collaborating with public research enables firms from other industries to diversify into the target industry, and second, because university researchers become academic entrepreneurs and enter the industry with their ventures (Audretsch et al., 2005).

In addition, firms in technologically advanced industries engage in various activities that help researchers and universities in related fields and disciplines. One important activity is lobbying. Often via industry associations taking the role of intermediates, 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.

Besides lobbying for public funds, many firms and industry associations spend substantial amounts of their own money to advance public research. After the ascent of the corporate R&D laboratory (Hounshell and Smith, 1988), large firms have frequently 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.

A detailed account of industry-science co-evolution is provided by Murmann (2003, 2013a, 2013b) in the historical context of the global 19th century synthetic dye industry. Murmann emphasizes the role of labor mobility between public research and the private sector. Academic entrepreneurship was particularly important at the outset of the industry, to the extent that the "list of early entrepreneurs in the British synthetic dye industry reads like an alumni directory of the Royal College of Chemistry in London" (Murmann, 2013a, p. 69). 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).

2.3 Co-evolution in regional systems of innovation?

Prior work suggests that the interaction of public research and private-sector R&D has a strong regional dimension. In particular, the notion of localized knowledge spillovers figures prominently in economic geography. Empirical studies suggest 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, an emphasis on finding regional collaboration partners is straightforward for both university researchers and private-sector firms. Co-located partners tend to be 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 PROs 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 in a given industry context co-evolve with the public research activities in the respective region. In the remainder of this paper, we 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

“Laser” is a generic term denoting spatially and temporally coherent light sources based on stimulated emission of photons. The virtually unbounded range of potential applications of laser technology were 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. Adapting lasers to new applications therefore turned out to be a major obstacle in the diffusion and commercial application of this technology. To date, new advances in laser technology have continued to open up new fields of use for which previously available laser sources were not applicable or not commercially viable.

The laser is a U.S. invention, but German university researchers and also private-sector 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 (blinded reference). Numbers of laser-related publications grew rapidly over the first two decades of laser research (blinded reference). 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, 2001). 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. This program was followed by the “Laser 2000” program (1993) and the broader “Optical Technologies” program (2002). Behind these programs was the ministry’s conviction that the German laser industry was lagging behind its international competitors. They 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) established in Aachen in 1985. The location of this institute was fiercely contested among the regional governments of three *Bundesländer* (cf. Fabian, 2011). 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, who was a member of the Fraunhofer Society's senate as well as of a commission that advised the government of Baden-Wuerttemberg on R&D policy. 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, Turmpf's Leibinger helped shape the agenda of the IfSW. He was also involved in the decision about who should be leading it (ibid.). In other cases such as the FLI, laser producers were directly involved as co-sponsors of the new institutes.

These events illustrate how laser firms influenced high-level decision making 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 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 3,273 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 (blinded reference). 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, PROs or individuals as applicants.

Laser-related scientific publications were analyzed by Fritsch and Medrano (2010) as well as in (blinded reference). 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 6,562 publications with two authors. For 1,291 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 established to focus on interaction 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 6,843 articles with three authors, we were able to retrieve at least two author affiliations in 2,179 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 7,764 cases. Not surprisingly, the share of co-authorships between public research and firms is larger for the articles with more than three authors. In this group it reaches 3.9 % (299 articles).

Taken together, patent and publication data thus indicate a modest level of direct interaction between different types of organizations.[4] Before concluding this section, we turn our attention to a different, more indirect kind of interaction between public research and private-sector R&D: mobility of graduates between public research and the private sector. We already noted above that some institutional co-publications may reflect earlier labor mobility by one of the involved authors. We now study this issue in a little more detail, focusing on the role of individuals who obtained doctoral degrees in laser-related research as inventors of patents related to laser sources. To this purpose, we conducted a text search 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 the field of laser research across disciplinary boundaries and in a database that consistently covers the entire time period under investigation. Excluding medical dissertations, in which lasers are frequently used only as research tools, our data encompass a total of 4,845 dissertations from 1960 to 2005 (cf. blinded reference, for details). We then matched the author names of these dissertations with the laser-related patent applications described above. Laser-educated inventors thus identified indeed 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 %. (blinded

[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.

reference) moreover identified 28 authors of laser-related dissertations among the founders of 143 laser producers that entered in Germany between 1960 and 2003, suggesting a non-negligible role of doctoral training in the breeding of future laser entrepreneurs.

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 substantial interaction 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. Our analysis builds on earlier research that has demonstrated the importance of regional university research for firm entry into the German laser industry (blinded reference). To allow 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), we estimate reduced-form vector autoregressive (VAR) models. 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 (blinded reference). As our proxy of laser-related R&D we again use the population of IPC H01S applications with German applicants at the German Patent Office from 1960 to 2005 (a total of 3,297 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 lasers as general purpose technologies utilized in a broad range of industrial applications.

We employ two alternative indicators of public research. Laser-related doctoral dissertations provide the first indicator. 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 (blinded reference) introduced in the previous section. For the econometric analysis, annual dissertation counts are aggregated to the university level. Alternatively, public research activities are measured by scientific publications. The publication dataset again corresponds to the one described above. Publications by authors with private-sector affiliations (which account for only a small share of the overall publication stock) were eliminated.

Planning regions (*Raumordnungsregionen* or ROR) are adopted as geographic units of analysis. 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 97 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.

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 the *Hochschulkompass,* 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 innovation and public research, we estimate a series of reduced-form panel vector autoregression models (VARs) (Sims, 1980). VARs are well-established as a methodology to study relationships between macroeconomic time series. They have also been applied to issues of industrial dynamics in recent years (cf., e.g., Broekel and Coad, 2012). In a reduced-form VAR, 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:

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

where *Z* is a vector including our measures of public research activities (alternatively measured by dissertation or publication counts), private-sector patent counts and the size of the regional population of laser source producers. Dissertation and publication data were aggregated for all universities located in the same planning region (ROR). We assume that dissertation projects have a duration of five years. For projects leading to publications or patents, we assume a three-year duration. State variables of the number of ongoing dissertation, publication and patent projects were constructed from the observable outcomes using these assumptions. This procedure provides us with an unbalanced panel data set with annual observations capturing the time period from 1960 to 2004.[5] To ensure stationarity and control for unobserved heterogeneity, all estimations are performed in first differences.[6]

Estimates from reduced-form panel VAR only show correlations, and not causal relationships, between the interdependent variables included in *Z*. Moreover, given that they do not reflect the

[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] Fisher-type tests did not reject the presence of unit roots in the original time series. For the first-differenced time series, the Null hypothesis of unit roots in all panels was rejected. 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.

interdependence among the contemporaneous variables, the individual coefficients in the 3x3-matrix *b* have no direct economic interpretation. Not even the sign of coefficients in a reduced-form VAR can be interpreted in a straightforward way (Hoover, 2001). However, reduced-form VAR models can be used 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. We therefore report the results of Granger causality tests for models with up to five lags ($s \leq 5$). P-values of these tests are shown in Table 3.[8]

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 (first column of left panel). We likewise find that patents are Granger-caused by the size of the regional laser firm population as well as by publications (second column of left panel). With the exception of producers 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 substantial co-evolution of firm population size, private-sector R&D and public research at the regional level.

Granger causality tests alternatively using regional dissertation counts as 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 adopt three strategies to assess the robustness of the above findings. First, the reduced-form VARs are re-estimated for shorter time periods. Second, the assumed duration of dissertation projects is varied. Third, 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

[7] The concept of Granger causality is based on testing 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.

[8] We focus on associations between the variables. Autocorrelations are mostly positive and significant.

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 causality 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).

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 6. 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 6, left panel). For the alternative proxy of dissertation projects, we now find consistently significant Granger-causal relationships running from public research to the regional firm population size (Table 6, 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. The results of these models with shorter assumed dissertation projects thus point to a substantial role of measurement error in our results. 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 uses a different statistical methodology. With the alleged impact of regional private-sector activities on public research it focuses on a key element of the proposed co-evolutionary dynamics. 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, which is obviously difficult to reconcile with the notion of regional co-evolution. The results of the hazard models can therefore only be taken as suggestive.

To estimate the hazard models, we first develop a risk set of suitable 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.[9] 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 7. Our baseline specification (Model 1 in Table 7) 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.[10] 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 empirical 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 on 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, 2013b) 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 rather high-level interactions that historians of science have focused upon, but can also be traced at the more mundane level of

[9] Very similar results were obtained when we alternatively assumed entry in the year of the department's first laser-related dissertation.
[10] Both variables are correlated. The patent variable is significant if the producer variable is dropped from the specification.

regional interactions. On the other hand, we have used micro-level panel data on various populations of relevant actors (firms, universities, 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 analysis 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 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. This conclusion raises 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? 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, we hope to answer questions like these in future research.

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Tables

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

Table 3: Results of Granger Causality tests (five-year dissertation duration) (first differences; 1960-2003)

	(p-values)	Δproducers	Δpatents	Δpublications	Δproducers	Δpatents	Δdissertations
	Δproducers	x	0.0218	0.0000	x	0.0108	0.0001
L1	**Δpatents**	0.0033	x	0.7808	0.0452	x	0.1627
	Δpub/ Δdiss	0.0000	0.0233	x	0.4902	0.5369	x
	Δproducers	x	0.0060	0.0000	x	0.0029	0.0007
L2	**Δpatents**	0.0000	x	0.0000	0.0001	x	0.0081
	Δpub/ Δdiss	0.0000	0.0057	x	0.3105	0.6742	x
	Δproducers	x	0.2238	0.0000	x	0.1887	0.0012
L3	**Δpatents**	0.0000	x	0.0000	0.0000	x	0.0134
	Δpub/ Δdiss	0.0000	0.0001	x	0.2777	0.3662	x
	Δproducers	x	0.0038	0.0000	x	0.0002	0.0000
L4	**Δpatents**	0.0000	x	0.0000	0.0000	x	0.0024
	Δpub/ Δdiss	0.0000	0.0003	x	0.3299	0.0004	x
	Δproducers	x	0.0007	0.0000	x	0.0000	0.0000
L5	**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 (five-year dissertation duration) (first differences, 1960-1982)

	(p-values)	Δproducers	Δpatents	Δpublications	Δproducers	Δpatents	Δdissertations
	Δproducers	x	0.0299	0.2097	x	0.0671	0.0276
L1	Δpatents	0.0000	x	0.1483	0.0000	x	0.0467
	Δpub/ Δdiss	0.0348	0.0974	x	0.4596	0.5713	x
	Δproducers	x	0.0444	0.0186	x	0.1885	0.0745
L2	Δpatents	0.0000	x	0.0023	0.0000	x	0.4973
	Δpub/ Δdiss	0.0506	0.0806	x	0.4524	0.0390	x
	Δproducers	x	0.5963	0.0107	x	0.9669	0.0218
L3	Δpatents	0.0000	x	0.0000	0.0000	x	0.2136
	Δpub/ Δdiss	0.0145	0.0008	x	0.6598	0.0060	x
	Δproducers	x	0.3682	0.1030	x	0.3836	0.0303
L4	Δpatents	0.0000	x	0.0003	0.0000	x	0.0256
	Δpub/ Δdiss	0.0089	0.0289	x	0.5696	0.0000	x
	Δproducers	x	0.0006	0.0960	x	0.0006	0.0005
L5	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 (five-year dissertation duration) (first differences, 1983 - 2003)

	(p-values)	Δproducers	Δpatents	Δpublications	Δproducers	Δpatents	Δdissertations
	Δproducers	x	0.0335	0.0000	x	0.0184	0.0021
L1	Δpatents	0.6747	x	0.3928	0.7006	x	0.2131
	Δpub/ Δdiss	0.0000	0.0006	x	0.7158	0.6610	x
	Δproducers	x	0.0329	0.0000	x	0.0172	0.0140
L2	Δpatents	0.0836	x	0.0002	0.0915	x	0.0057
	Δpub/ Δdiss	0.0000	0.0025	x	0.3667	0.2560	x
	Δproducers	x	0.3607	0.0000	x	0.1500	0.0033
L3	Δpatents	0.0000	x	0.0001	0.0000	x	0.0005
	Δpub/ Δdiss	0.0000	0.0001	x	0.3827	0.1815	x
	Δproducers	x	0.0027	0.0000	x	0.0001	0.0000
L4	Δpatents	0.0000	x	0.0000	0.0000	x	0.0004
	Δpub/ Δdiss	0.0000	0.0000	x	0.4926	0.0033	x
	Δproducers	x	0.0000	0.0000	x	0.0000	0.0002
L5	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.

Table 6: Results of Granger Causality tests (four-year dissertation duration) (first differences; 1960-2004)

	(p-values)	Δproducers	Δpatents	Δpublications	Δproducers	Δpatents	Δdissertations
	Δproducers	x	0.0263	0.0000	x	0.0139	0.0014
L1	Δpatents	0.1149	x	0.3552	0.0096	x	0.1068
	Δpub/ Δdiss	0.0000	0.0150	x	0.2833	0.1588	x
	Δproducers	x	0.0090	0.0000	x	0.0035	0.0054
L2	Δpatents	0.1525	x	0.0004	0.0213	x	0.1334
	Δpub/ Δdiss	0.0000	0.0034	x	0.0331	0.0442	x
	Δproducers	x	0.1969	0.0000	x	0.1225	0.0098
L3	Δpatents	0.2413	x	0.0000	0.0315	x	0.5254
	Δpub/ Δdiss	0.0000	0.0000	x	0.0000	0.1763	x
	Δproducers	x	0.0029	0.0000	x	0.0001	0.1946
L4	Δpatents	0.3490	x	0.0000	0.0636	x	0.0089
	Δpub/ Δdiss	0.0000	0.0002	x	0.0000	0.0013	x
	Δproducers	x	0.0001	0.0000	x	0.0000	0.3098
L5	Δpatents	0.4325	x	0.0000	0.1706	x	0.0069
	Δpub/ Δdiss	0.0000	0.0019	x	0.0000	0.0037	x

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

Table 7: Results: Hazard of departmental entry into laser research (1960-2004).

	Model 1	Model 2	Model 3	Model 4
Laser producers	0.3859***		0.3434**	0.2630*
	(0.1134)		(0.1389)	(0.1505)
TU*laser producers		0.2950***		
		(0.0601)		
Uni*laser producers		0.5647**		
		(0.2278)		
Laser patents			0.0174	0.0201
			(0.0343)	(0.0355)
Engineering department				-0.2268
				(0.2839)
Pop. density (log)				0.3970**
				(0.1778)
Observations	2119	2219	2119	2119
(subjects)	(84)	(84)	(84)	(84)
Log-likelihhod	-186.6462	-185.7728	-186.4901	-183.8072
p < chi^2	0.0007		0.0031	0.0010

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