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Technological and geographical knowledge spillover in the German empire 1877–1918

By JOCHEN STREB, JÖRG BATEN AND SHUXI YIN

SUMMARY

We use a newly developed data set of 39,343 high-value patents granted between 1877 and 1918 to demonstrate that technological progress during German industrialization occurred in at least four different technological waves. We distinguish the railway wave (1877–86), the dye wave (1887–96), the chemical wave (1897–1902), and the wave of electrical engineering (1903–18). Evidence is presented that inter-industry knowledge spillovers between technologically, economically, and geographically related industries were a major source for innovative activities during German industrialization. We also show that technological change affected the geographical distribution of innovative regions. Using an index of technologically revealed comparative advantage we find that regions that increased their innovativeness during the waves of technological progress revealed special strength in technological clusters like electrical engineering, mechanical engineering, or chemicals.

I

One of the most interesting problems of economic history is still the question why some nations were able to industrialize successfully and others were not. In general, industrialization can be characterized as the transition process that leads an economy from stagnation to sustainable growth.[1] Mokyr suggests that the key factor in this transition is a fundamental change in the behaviour of economic actors, who have to develop both the willingness and the ability to create a permanent stream of innovations that shifts the production frontier, which is determined by the efficient use of the resources land, labour, and capital, steadily outwards.[2] North and Thomas stress that the willingness to innovate depends on the efficiency of institutional arrangements that are supposed to channel individual economic effort in the socially most-profitable activities.[3] According to this view the liberal reforms of the nineteenth century that defined property rights with respect to land, real capital, and finally inventions

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[1] See Landes, *Unbound prometheus.*

[2] See Mokyr, *Lever of riches*, p. 4

[3] See North and Thomas, *Rise of the western world*, p. 2.

clearly were a necessary precondition for the industrialization of Germany. Keck adds that during the German industrialization the ability to innovate was considerably increased by new organizations such as an advanced education system, public research organizations, and industrial research departments.[4] Despite the general consensus among economic historians that the application of new technological knowledge was the prime source for overcoming economic stagnation, not much is known about the concrete timing of innovations and their distribution over industries and regions during the German industrialization.[5]

The diffusion of new technological knowledge might be as important as its creation to make an economy grow.[6] This is especially true for knowledge spillovers that increase the productivity of firms in the technological or geographical neighbourhood of the original inventor.[7] Jacobs believes that the most important knowledge spillovers take place across industries in highly diversified industrial regions.[8] This argument has received further support from studies that point out that technological solutions are often transferred from the sector where they were originally invented to a variety of industries applying them.[9] In this respect Lundvall emphasizes the importance of inter-industry knowledge spillovers between suppliers and customers.[10] However, except for some anecdotal evidence regarding the information exchange between German dye producers and textile firms in the late nineteenth century,[11] not much is known about the actual impact of knowledge spillovers during the German industrialization.

The purpose of this article is to find evidence for important technological and geographical knowledge spillovers during German industrialization. Our research hypotheses are:

1. Patent booms in leading technological sectors accelerated innovating activities in technologically related industries via knowledge spillovers.
2. Knowledge spillovers between technologically related industries were considerably facilitated by geographical proximity.

We base our analysis on a newly developed data set of 39,343 high-value patents granted between 1877 and 1918. To highlight both the potential and the limits of our database we will address in the following not only its merits, but also its shortcomings.

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[4] See Keck, 'National system'.

[5] See Metz and Watteler, 'Historische Innovationsindikatoren', pp. 37–41. For patenting activities during the British and American industrialization see Khan and Sokoloff, 'Patent institutions'; MacLeod, *Inventing the industrial revolution*; Sokoloff, 'Inventive activity'.

[6] See Streb, 'Shaping the national system'.

[7] For a survey on knowledge spillovers see Griliches, 'Search for R&D spillovers'.

[8] See Jacobs, *Economy of cities*.

[9] See Bairoch, *Cities and economic development*; Scherer, 'Inter-industry technology flows'.

[10] See Lundvall, 'System of innovation'.

[11] See Beer, *German dye industry*. See also Streb, *Technologiepolitik*, pp. 75–6.

Much is said about the shortcomings of patents as a measure for technological progress. Griliches has stated: 'Not all inventions are patentable, not all inventions are patents and the inventions that are patented differ greatly in 'quality', in the magnitude of inventive output associated with them.'[12] The first part of this statement refers to the well-known fact that the propensity to patent varies across industries. Levin et al., for example, discovered that some industries try to appropriate the returns of their inventions primarily by keeping them secret, while others, like the chemical or pharmaceutical industries, prefer patenting instead.[13] Because of the different propensities of industries to patent, it might be misleading to interpret a particular industry's comparatively high number of patents automatically as a sign for its alleged above-average innovativeness. The problem that is addressed in the second part of Griliches' statement is probably the more serious one. Pure patent counts allocate the same weight to every patent, no matter whether it has a high or a low economic value for the patentee or the society. Using the number of patents as an indicator for new technological knowledge suitable to foster economic growth therefore leads to a potentially very large measurement error.[14] To decrease this measurement error it is necessary to distinguish patents with a high economic value from those with a low value. A possibility way of doing this is to let the patents be evaluated by experts. Townsend, for example, rated patents related to coal mining according to their importance, on a scale from 1 to 4.[15] This procedure might be recommendable for specific industry studies with a small number of observations, but does not work for large patent populations where the careful evaluation of every single patent would be very time-consuming and would require engineering competence in a wide range of technological fields.

Our population of 311,019 patents granted between 1877 and 1918 definitely belongs to the latter group. The starting year of the observation period is determined by the establishment of the German patent law of 1877[16] that made it possible for inventors to apply for patent protection not only in single states, but in the whole German Empire.[17] The patent protection could last up to fifteen years, but was not free. Rather, the patentee had to pay an increasing renewal fee at the beginning of each year in order to keep his patent in force. This annual renewal fee came to 50 marks in the

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[12] Griliches, 'Patent statistics', p. 1669. See also Archibugi, 'Patenting'.

[13] See Levin et al., 'Appropriating the returns'. See also Arundel and Kabla, 'What percentage?'.

[14] The academic debate about the extent of this kind of measurement error is still unsettled. On the one hand, Schankerman and Pakes state that 'one cannot draw inferences on changes in the value of cohorts of [European] patents . . . from changes in the quantity of patents during this period' [1955–1975]. Schankerman and Pakes, 'Value of patent rights in European countries', p. 1070. Sullivan, on the other hand, shows that for the 1852–76 period fluctuations of the number and aggregate value of British and Irish patents generally moved in the same direction. See Sullivan, 'Value of patent rights in Great Britain and Ireland', p. 49.

[15] See Townsend, 'Innovation in coal-mining', p. 150.

[16] See 'Patentgesetz vom 25. Mai 1877', *Reichsgesetzblatt*, (1877), pp. 501–10.

[17] For the genesis of the German patent law see Heggen, 'Vorgeschichte des Reichspatentgesetzes'.

first two years,[18] and grew then by 50 marks each year, up to 700 marks at the beginning of the fifteenth year. A patent holder was supposed to decide to renew his patent only when the costs of doing this were lower than the expected future returns of the patent. Using this contemporary assumption about the behaviour of patent holders, we will use information on the actual lifespan of a patent as an indicator of its private economic value.[19]

Our prime data source is the annual 'Verzeichnis der im Vorjahre erteilten Patente' published by the German patent office, which lists all patents granted in the preceding year, including the technological class of the invention, and the name and location of the patent holder.[20] The latter information allows us to tell whether a particular patent was held by a German or foreign patentee, by a private inventor, or by a firm. The regular publication also contains a list of all patents still in force, which enables us to calculate the lifespans of particular patents. We organize the remaining paper in three main sections. Section II explains the renewal decision of a patentee and shows under which circumstances the different lifespans of patents can be used to identify the high-value patents of German industrialization. Section III analyses the technological distribution of high-value patents over time. We will identify four successive patent waves in industrializing Germany during which knowledge spillovers occurred between technologically related industries. Section IV discusses how technological change described by these patent waves affected the geographical distribution of innovative regions. It will turn out that the most innovative regions relied on diversified industry clusters in the fields of mechanical or electrical engineering, or chemicals.

II

Under the patent law of the German Empire a patentee had to decide annually whether he was going to renew his patent for another year or not. The outcome of this decision depended on the patentee's expectations about the future returns and costs of holding the patent. The latter were determined by the renewal fees demanded by the patent office, and were therefore foreseeable with certainty. In contrast, the future returns of a patent were highly uncertain. They could arise from two major sources. On the one hand, a patentee could use a patent to increase his profits by selling his innovation as a temporary monopolist or by licensing another producer to do so. On the other hand, a patentee could also use his patent to prevent

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[18] In the first year the potential patentee had to pay 20 marks for the application and an additional 30 marks after the patent was granted. The monthly gross income of the average industrial worker was approximately 50 marks. See Bry, *Wages in Germany*, p. 51.

[19] Schankerman and Pakes were the first who used the life-span of patents to estimate their private economic value. See Schankerman and Pakes, 'Value of patent rights in European countries'.

[20] For a survey on the publications of the Reichspatentamt see Theobald, 'Veröffentlichung des Reichspatentamts'.

sales of competitors' innovations that had the potential to decrease the market share of his own already-established products. In 1911, for example, Siemens succeeded in developing the first light bulb with a metallic filament based on tantalum. Two years later Siemens was granted the two long-lived German patents no. 153328 and 154527 that proved to be the base from which the German firm gained the leading role in the world market. The sales of tantalum light bulbs gradually increased from 240,000 units at the beginning to almost 10 millions units in 1912. Even after General Electric discovered the superior wolfram light bulb, the tantalum light bulb patents did not loose their high economic value, since Siemens was able to barter them for the very valuable patents of General Electric. The American firm was forced to accept this patent exchange because of the Siemens threat to use its own patents to hinder General Electric's entry into the German market.[21]

We assume that the patent holders renewed their patent if and only if the present value of the expected future returns exceeded the present value of the future costs either for the remaining maximum lifespan of the patent or for at least a shorter sub-period. This condition is satisfied when the following inequality holds for at least one combination of *t* and *T*.

$$\sum_{t}^{T} E(R_t)(1+r)^{T-t} > \sum_{t}^{T} C_t(l+r)^{T-t} \quad \textit{with} \;\; t=\{1,\ldots,15\}, T=\{1,\ldots,15\}, T \geq t \qquad (1)$$

$E(R_t)$ denotes the expected returns in year t, C_t the costs in year t, T the remaining lifespan of the patent, t the first year of the remaining lifespan, and r the interest rate used to discount the future values.

Since patents can generate increasing or decreasing revenues over time it is unavoidable to compare the expected present values of future costs and revenues for both the maximum lifespan and all shorter sub-periods. Let us first consider the case of a patent that produces very high returns in the last years of its maximum lifespan, but very low returns in the years before. As a result, the present value of the expected net revenues of the maximum lifespan might be positive, but the ones of shorter sub-periods might be negative. That is why a patent holder who bases his renewal decision only on his expectations about the next year could make the mistake of giving up an apparently worthless patent, which would be in fact very profitable in the future. In the case of a patent with decreasing returns over time the opposite is true, because this kind of patent might have a negative present value of expected net revenues for its maximum lifespan but a positive one for shorter sub-periods.

A long lifespan of a historical patent undoubtedly indicates its comparatively high private economic value. This conclusion, however, does not imply that all high-value patents had a long lifespan. There might have been

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[21] See Erker, 'Verwissenschaftlichung der Industrie', p. 75–7.

patents with fast decreasing returns over time that were given up after just a few years, but nevertheless yielded high returns to the patent holder in their comparatively short lifespan. That is why the criterion lifespan, which systematically sorts out all short-lived patents, is not a perfect measure to identify high-value patents.[22] However, using the lifespan of patents to distinguish low-value from high-value patents is still a reasonably working procedure because it identifies all high-value patents with increasing returns and all long-lived high-value patents with decreasing returns. This method is additionally justified by the fact that the distribution of lifespans of patents is highly skewed to the right.

In an early stage of an innovation process an inventor is often highly uncertain whether or not his idea can be profitably exploited in the future. The low renewal fees at the beginning of a patent's life allow the inventor to use the patent as a comparatively cheap option that protects his new knowledge and gives him the time to learn more about the technological and economic prospects of his invention.[23] Pakes states, first, that this learning process of the patent holders is concentrated in the early years of a patent's lifespan, and second, that most of these options turn out to be worthless.[24] These assumptions were supported by our finding that approximately 70 per cent of all German patents granted between 1891 and 1907 had already been cancelled after just five years. After the fifth year, the speed of patent cancellation decelerates. About 10 per cent of all patents were still in force after ten years, 4.7 per cent of all patents reached the maximum age of 15 years.

A basic question about the lifespan approach is how many years a patent had to be in force to be interpreted as a high-value patent. Schankerman and Pakes, who invented the method of using survival rates as an indicator for high-value patents, came to the conclusion that most of the value of the patent stock built up in the post-World War II period in Britain, France, and Western Germany was concentrated in the upper 5 per cent of the long-lived patents.[25] Following this suggestion would mean in our case selecting only those patents that reached the maximum life span of 15 years. To decrease the potential selection bias caused by high-value patents with decreasing returns, we instead chose to follow Sullivan, who explored British and Irish patents of the second half of the nineteenth century, and to interpret the upper 10 per cent of the long-lived patents as the high-value patents of our total patent population.[26] Exploiting the information given by the survival rate in figure 1, we therefore selected all patents that survived

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[22] The extent of this selection bias depends on the actual share of patents with fast decreasing returns in the population of all high-value patents. Schankerman and Pakes assume decreasing returns for all patents to make their maths work. See Schankerman and Pakes, 'Value of patent rights in European countries', p. 1054.

[23] See Pakes, 'Patents as options'.

[24] See ibid., pp. 772–3.

[25] See Schankerman and Pakes, 'Value of patent rights in European countries', p. 1067.

[26] See Sullivan, 'Value of patent rights in Great Britain and Ireland', p. 49.

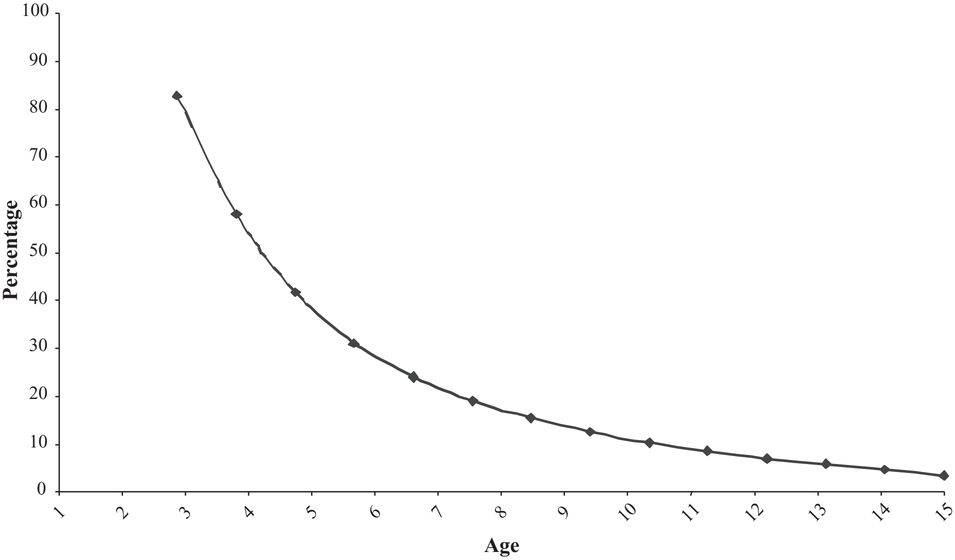

Figure 1. *The survival rate of German patents*[a]

Note: a This calculation is based on information on the patent cohorts 1891–1907. See *Blatt für Patent-, Muster- und Zeichenwesen* (1914), p. 84.

at least ten years.[27] This selection process resulted in a sample of 39,343 patents, which we interpret as the high-value patents of the German Empire in the following. Figure 2 shows how many patents and high-value patents respectively were annually granted between 1877 and 1918.

The number of patents granted annually quickly rose to about 4,000 after the establishment of the German patent law and stayed at this level until the late 1880s. The patent rush of the 1890s was probably triggered by a change in patent law that particularly improved the patent protection of chemical inventions. The patent law of 1877 had determined that chemical firms could only patent new processes but not the new products made by these processes. As a result, foreign chemical firms were able to circumvent this kind of patent protection by producing the new products with the new processes abroad and selling them in the German market. To impede such behaviour the new German patent law of 1891[28] stipulated that patents granted for new chemical processes also protected the products produced by these processes.[29] Thereafter the number of patents in the technological fields of chemicals increased considerably. The growing number of patents

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[27] We did not have the personnel to find out the individual lifespan for each of more than 300,000 patents.

[28] See Patentgesetz vom 7. April 1891, *Reichsgesetzblatt* (1891), pp. 79–90, especially § 4.

[29] See Bruchhausen, 'Der lange Weg zum modernen Patentrecht'. See also Fleischer, *Patentgesetzgebung*, pp. 164–7.

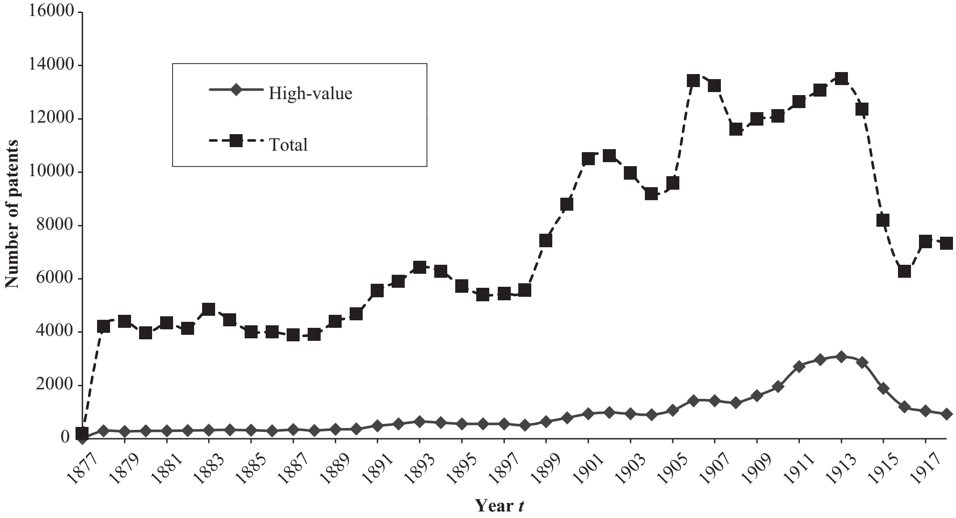

Figure 2. *Patents and high-value patents annually granted between 1877 and 1918*
Source: Baten/Streb database (see text)

was probably also caused by the fact that the new German patent law of 1891 improved the efficiency of the patent office by making the technicians—who decided about the novelty of patent application, and had until then only worked part-time for the patent office—into full-time and lifelong employees.[30] At the beginning of the twentieth century the number of patents granted per year exceeded 10,000 for the first time.

The average share of high-value patents in the total of all patents granted between 1877 and 1918 was 11.14 per cent. As we can see in table 1, the actual annual share, however, was not constant over time. Rather, the annual share of high-value patents slowly increased between 1877 and 1893 from 5.3 per cent to 10 per cent, stagnated in the following 15 years, and then skyrocketed up to more than 23 per cent on the eve of World War I.

How can the slow rise in the share of high-value patents between 1877 and 1893 be explained? It is conceivable that the contemporary inventors, who were not familiar with the newly introduced patent law at the beginning, improved their capabilities to judge the future economic prospects of their inventions correctly step by step. As a result of this learning process, the share of low-value patents actually applied for would have decreased over time. An alternative explanation, however, is based on the patent office's observation that the relation of firms' professional research workers and private amateurish inventors who more likely applied for low-value

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[30] See Kaiserliches Patentamt, *Geschäftsthätigkeit*, p. 158.

Table 1. *The share of high-value patents in all patents granted per year*

Year	*Share (%)*	*Year*	*Share (%)*	*Year*	*Share (%)*
1877	5.3	1891	8.8	1905	11.1
1878	7.1	1892	9.5	1906	10.6
1879	6.2	1893	10.0	1907	10.7
1880	7.5	1894	9.7	1908	11.7
1881	6.8	1895	9.9	1909	13.5
1882	7.5	1896	10.2	1910	16.2
1883	6.7	1897	10.4	1911	21.4
1884	7.4	1898	9.2	1912	22.7
1885	7.9	1899	8.7	1913	22.8
1886	7.4	1900	9.0	1914	23.2
1887	8.9	1901	9.0	1915	23.1
1888	8.0	1902	9.3	1916	19.1
1889	8.2	1903	9.4	1917	14.1
1890	8.0	1904	9.8	1918	12.6

Source: Baten/Streb database (see text)

patents was not the same in every technological class.[31] Classes such as hat making (class 41), haberdashery (class 44), or harnesses (class 56) were rather dominated by over-optimistic amateurs, and had therefore a below-average lifespan of patents. Most inventions of technological classes with an above-average lifespan of patents, such as dyes (class 22) or chemicals (class 12), were developed by industrial R&D departments. Since—as we will show below—the share of the latter classes in the total number of patents considerably increased in the 1880s, the growing share of high-value patents was probably caused by the relatively decreasing inventing activity of amateur inventors.

The uncertainty of inventors, however, cannot be totally reduced. Mokyr points out: ‘After all, technological change ventures into the unknown, not into the uncertain. The risk cannot be diversified away.’[32] That is why firms were still forced to invest in some patents that finally turned out to be worthless, in order to preserve a reasonably high probability of getting one of the rare high-value patents. The stable share of high-value patents in the patent population of about 10 per cent in the 1890s and early 1900s might imply that the patenting firms had found an appropriate compromise between the goals avoiding costs for low-value patents and keeping the chance of getting a high-value patent. This success rate of 10 per cent is, of course, not an independent empirical fact, but resulted from our decision to define high-value patents as those that lasted at least ten years. Nevertheless, it is an interesting coincidence that Pavitt holds the view that usually about 10 per cent of all industrial R&D projects lead to a commercial success.[33]

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[31] See ibid., pp. 205–7.

[32] Mokyr, *Lever of riches*, p. 284.

[33] See Pavitt, ‘Key characteristics’.

Table 2. *Wholesale prices and renewal fees during the German industrialization, 1914–23, 1913 = 100*[a]

Date	*Wholesale prices*	*Renewal fee for the 10th year*
1914	105	100
1915	142	100
1916	152	100
1917	179	100
1918	217	100
1919	415	100
1920	1,486	100
June 1921 / July 6, 1921[b]	1,428	156
June 15, 1922 / June 27, 1922[b]	6,775	667
November 25, 1922	122,919	3,333
March 24, 1923	482,700	46,667
July 10, 1923 / July 9, 1923[b]	4,864,400	222,222
Sept. 4, 1923 / Sept. 2, 1923[b]	298,153,200	11,111,111
Oct. 30, 1923 / Oct. 29, 1923[b]	1,865,850,000,000	69,111,111,111

Notes: a Statistisches Reichsamt, ed., *Statistisches Jahrbuch*, pp. 284 f. *Blatt für Patent-, Muster- und Zeichenwesen*, various years. *b* The first date refers to the wholesale prices, the second to the renewal fee.

The boom in high-value patents in the pre-World War I years could be interpreted as an anomaly brought about by the German inflation of the post-World War I years. Table 2 shows that in this period wholesale prices increased much faster than the renewal fees of the patents, which implies that the deflated present values of the patent costs decreased considerably between 1914 and 1923. As a result, more patents could have been judged to be worth renewing than would have been the case in a situation without inflation.

A detailed analysis of the annual mortality rates of the patent cohorts 1902–24, depicted in table 3, however, shows that this inflation story is wrong. The rows of table 3 show the annual mortality rate of a particular patent cohort during its lifespan. For example, the number 17.4 in the upper left cell means that of all new patents granted in 1902 only 82.6 per cent were renewed at the beginning of the year 1903. Of those prolonged patents, in 1904 again 26.9 per cent were not prolonged. The columns present the annual mortality rate in a particular age of the patents for different patent cohorts. Column 1, for example, reveals that the mortality rate of the patent cohort 1902 was higher in the first year than the respective rate of the patent cohort 1903, which was only 15 per cent. In table 3, numbers for the years 1915 to 1918 numbers are in bold. So we can see easily that in both the columns and the rows the annual mortality rates already decreased in 1915, kept their low level during the whole of First World War, but increased again during the years of high inflation. This sharp drop in mortality rates resulted from a governmental decision to exempt the patentees from

Table 3. Mortality rates of the patent cohorts 1902–24 in year t *of their lifespan, as a percentage of the patents still active in the preceding year (for 1915–18 numbers in bold)*

Cohort	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
1902	17.4	26.9	27.5	24.5	21.8	23.0	19.3	16.9	14.2	15.7	15.6	18.6	18.4	**9.7**
1903	15.0	24.4	25.7	24.3	24.0	22.4	17.2	19.5	16.3	18.3	17.5	16.3	**16.7**	**9.6**
1904	14.1	22.6	26.6	26.9	23.2	20.4	18.1	15.6	17.0	27.7	26.4	**10.3**	**7.2**	**24.0**
1905	14.2	25.5	28.0	27.7	23.3	19.9	17.1	18.1	24.3	24.9	**11.1**	**6.0**	**8.4**	**45.2**
1906	15.1	28.4	28.4	26.7	23.2	19.6	18.3	24.6	26.4	**10.4**	**4.9**	**10.3**	18.6	30.3
1907	15.7	26.7	27.8	24.0	20.8	19.5	24.0	25.3	**10.6**	**3.6**	**6.1**	**8.0**	17.4	31.4
1908	15.5	25.2	26.1	24.0	19.8	28.7	23.1	**8.9**	**3.1**	**11.4**	**9.4**	15.8	26.8	29.0
1909	15.4	22.8	24.3	24.3	27.4	21.0	**14.1**	**3.9**	**11.0**	**20.6**	23.8	24.5	40.4	47.6
1910	14.6	22.4	24.5	32.3	29.5	**5.7**	**2.9**	**7.2**	**11.3**	15.6	27.3	19.0	23.9	16.5
1911	15.5	24.2	34.4	24.3	**6.0**	**3.9**	**7.5**	**13.6**	19.2	31.8	19.7	26.4	24.7	9.7
1912	15.1	36.1	22.5	**6.2**	**3.1**	**5.1**	**14.1**	23.4	35.8	15.9	37.8	36.6	10.9	7.8
1913	16.5	30.1	**5.4**	**3.3**	**6.1**	**9.3**	20.6	34.2	18.3	22.6	28.8	19.2	20.1	12.5
1914	10.8	**15.9**	**3.8**	**3.3**	**11.4**	13.1	37.9	17.7	23.4	23.3	11.1	17.0	15.6	10.9
1915	**9.2**	**7.4**	**2.7**	**5.0**	20.9	31.0	19.9	28.6	25.3	17.6	16.7	12.7	16.1	13.3
1916	**6.7**	**3.7**	**4.3**	13.3	28.1	28.5	25.5	31.9	21.5	19.5	15.7	17.2	22.4	22.1
1917	**6.3**	**3.5**	13.2	27.3	24.7	32.2	43.1	23.0	25.2	20.3	24.7	28.3	39.5	39.4
1918	**0.8**	1.4	8.7	25.4	23.1	24.7	41.1	28.7	18.1	17.0	17.9	18.5	22.6	32.6
1919	0.3	5.3	20.0	22.8	21.4	35.3	22.5	28.3	15.7	17.8	18.7	21.2	30.0	19.1
1920	1.2	11.2	15.5	21.2	31.5	21.9	15.7	13.0	13.7	17.1	17.3	25.5	17.2	20.5
1921	1.5	8.8	17.1	32.0	24.5	18.9	15.9	16.3	19.3	22.5	31.3	20.6	22.2	17.5
1922	1.4	9.8	25.2	22.3	18.9	16.9	17.1	17.8	21.4	30.6	22.7	21.0	13.7	11.3
1923	1.7	13.4	17.2	17.4	16.2	17.6	18.6	20.3	29.0	21.8	21.3	14.2	9.3	9.6
1924	2.4	9.6	13.8	14.8	16.4	18.7	20.4	28.0	23.2	22.2	14.6	21.1	2.1	7.4

Source: Blatt für Patent-, Muster- und Zeichenwesen, various years.

renewal fees during wartime.[34] Obviously, a lot of patentees who would otherwise have decided to give up their patents took the chance to prolong them for free, thereby creating the boom of high-value patents between 1910 and 1917 depicted in table 2. This behaviour goes very well with our basic assumption that the increasing renewal fees were the major reason for a patentee's decision not to prolong his patent.

III

Patents can be assigned to the industry in which they were developed, or to the industry that will use or produce the resulting products and whose productivity may thereby increase.[35] New dyes, for example, usually originated in chemical firms, but were used by textile producers. The technological classes assigned to the patents by the German patent office mostly

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[34] See 'Bekanntmachung, betreffend vorübergehende Erleichterungen auf dem Gebiete des Patent-, Gebrauchsmuster- und Warenzeichenrechts vom 10. September 1914', *Blatt für Patent-, Muster- und Zeichenwesen*, (1914), p. 290; 'Bekanntmachung, betreffend weitere Erleichterungen auf dem Gebiete des Patent- ud Gebrauchsmusterrechts vom 31. März 1915', *Blatt für Patent-, Muster- und Zeichenwesen*, (1915), p. 118.

[35] See Scherer, 'Inter-industry technology flows', pp. 228–9.

corresponded to the industry that was supposed to use the respective invention. However, the correspondence between the technological class and the industry that might profit by the patent was far from perfect. A major shortcoming was that patents were assigned to only one technological class although they were often useful in several industries. New inventions with respect to steam engines, for example, were allocated to technological class 14, but probably increased the profits in a wide range of industries that used this kind of engine as a source for kinetic energy. Table 4 lists the 18 technological classes that contained the largest number of high-value patents of all 89 classes in the period between 1877 and 1918.

This ranking could lead to the impression that during German industrialization technological progress mainly relied on electrical engineering, chemicals, including dyes, and scientific instruments, which together included more than one-quarter of all high-value patents. Three arguments stand against this simple conclusion. First, we have already mentioned that industries such as electrical engineering or chemicals generally seem to have a higher propensity to patent their inventions than, for example, the machine and vehicle industry, which above all tries to protect inventions by keeping how to make them secret. Second, the technological classes of the German patent law differed considerably in the width of the technological field they covered. Patents in the fields of electrical engineering and chemicals were concentrated in classes 21 and 12, or 22 respectively, whereas patents with regard to mechanical engineering were spread over several classes such as 47 (machine parts), 49 (metal processing), 14 (steam engine), or 63 (vehicles). What is more, 'machinery patents' could also be

Table 4. *Ranking of technological classes 1877–1918*

Rank	*Class*	*Number of high-value patents*	*Share in all high-value patents (%)*	*Cumulated shares (%)*
1	21 Electrical engineering	3350	8.51	8.51
2	12 Chemicals (without dyes)	2840	7.22	15.73
3	22 Dyes	2206	5.61	21.34
4	42 Scientific instruments	1584	4.03	25.37
5	15 Printing	1429	3.63	29.00
6	49 Metal processing	1202	3.06	32.06
7	20 Railway installations	1146	2.91	34.97
8	47 Machine parts	1137	2.89	37.86
9	72 Firearms	1003	2.56	40.42
10	8 Dyeing	928	2.36	42.78
11	45 Agriculture	904	2.30	45.08
12	52 Sewing	706	1.79	46.87
13	80 Earthenware	675	1.72	48.59
14	46 Internal combustion engines	627	1.59	50.18
15	30 Health care	615	1.56	51.74
16	13 Steam boiler	605	1.54	53.28
17	81 Transportation	601	1.53	54.81
18	14 Steam engine	553	1.41	56.22

Source: Baten/Streb database (see text)

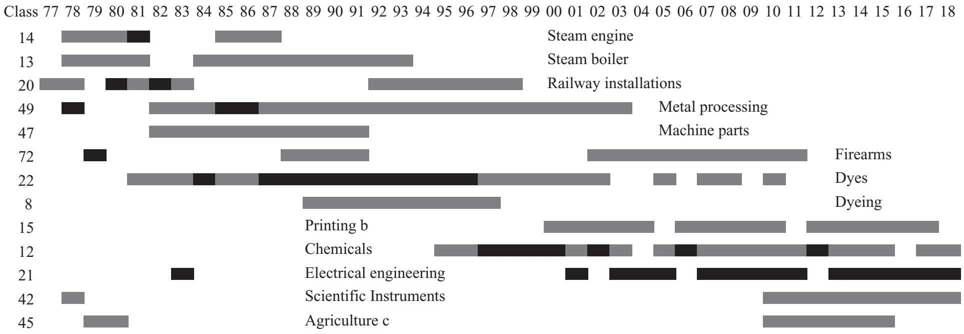

Figure 3. *The major patent booms 1877–1918*[a]

Notes: a Figure 5 does not contain the less-important technological classes 6 (brewery, rank 2 in year 1877, average rank 31), 36 (heating systems, rank 2 in 1878, average rank 35), 68 (metal-working, rank 1 in 1877, average rank 40), 76 (spinning, rank 3 in 1881, average rank 25) and 89 (sugar, rank 2 in 1879, average rank 44). *b* The highest rank of printing was 4. *c* The highest rank of agriculture between 1910 and 1915 was 5.
Source: Baten/Streb database (see text)

found in less obvious classes such as 45 (agriculture → agricultural machinery) or 86 (weaving → textile machines), to name just a few. This last finding also implies that it is not advisable to try to calculate the accurate number of 'machinery patents' just by aggregating some technological classes as Hoffmann did for 'metal working' on basis of all patents granted.[36] Third, our sample is dominated by the many high-value patents of the pre-World War I boom, during which electrical engineering patents especially flourished. As a result, electrical engineering has gained the leading position in table 3, even though this technological class was not dominating patenting activity in the decades before 1900. These three observations together lead to the conclusion that technological progress in the broad technological field of mechanical engineering played a much greater role during German industrialization than table 4 might suggest.

We are able to solve most of these problems by analysing the patenting activities in the 89 technological classes over time. It turns out that the ranking of the technological classes presented in table 4 was not constant between 1877 and 1918. In general, different technological classes boomed in different sub-periods. Figure 3 shows this finding by showing the major patent booms between 1877 and 1918. A major patent boom of a specific technological class is defined as the period in which this technological class held an annual rank no less than its average rank[37] in every year, and one of the three highest ranks in at least one year of this period.

Patent booms of specific technological classes were generally marked by grey bars. In years in which a technological class was ranked first this bar

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[36] See Hoffmann, *Wachstum der deutschen Wirtschaft*, pp. 264–9.
[37] The average rank of a technological class is shown in tab. 4.

is coloured black. We can distinguish four different waves of technological progress:

1. the railway wave (1877–86),
2. the dye wave (1887–96),
3. the chemical wave (1897–1902),
4. the wave of electrical engineering (1903–18).

The railway wave was dominated by patents in the technological classes steam boiler (class 13), steam engine (class 14), railway installations (class 20), which also contained inventions concerning rail tracks, rail switches and signals, machine parts (class 47), and metal processing (class 49). Traditionally, the railway industry is regarded as Germany's leading sector in the middle of the nineteenth century that, by increasing demand for coal, iron and advanced engineering technology, caused the parallel growth of the German coal mining, iron and steal industry, and mechanical engineering.[38] Our finding supports the conjecture that the railway industry generated forward and backward linkages not only by selling or buying tangible goods and services, but also played an important role as a focal point for the exchange of intangible new technological knowledge in the field of mechanical engineering, indicated by the patent boom in most of the industries of the railway cluster between 1877 and 1886.

The industries of the railway cluster kept to their above-average patenting activities until the beginning of the twentieth century. This did not prevent, however, the new industries of the second industrial revolution, namely chemicals and electrical engineering, taking over the technological lead in the mid-1880s. According to Murmann's co-evolutionary approach, the meteoric rise of the German dye industry was paradoxically caused both by the absence of a German patent law before 1877, and by its existence afterwards.[39] The absence of patent protection led in the 1860s and 1870s to a much higher number of newly founded dye producers in Germany than in Britain or the United States, where entry barriers were substantial because of an already-existing patent law. The initially high number of German dye producers resulted in a fierce price competition, in which only those firms that were able to cut costs considerably survived. After the establishment of the German patent law in 1877, the winners of this selection process gave up their traditional strategy of imitating new dyes by foreign inventors, and instead used their substantial profits to build up industrial laboratories, in which, for the first time in economic history, white-collar workers searched systematically and based on the division of labour for economically useful inventions.[40] As a result, the German dye producers considerably accelerated the evolution of synthetic dye technology by inventing famous dyes such as 'Congo Red' and 'Synthetic Indigo'.

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[38] See Fremdling, *Eisenbahnen*, p. 5.

[39] See Murmann, *Knowledge*, pp. 84–93.

[40] See Meyer-Thurow, 'Industrialisation of invention'.

They also succeeded in shaping their institutional environment by lobbying for the change of patent law in 1891 explained above. The German chemical firms' new and surprisingly modern attitude towards innovating and patenting activities is revealed in a statement by Duisberg, a former chief executive of Bayer:

> On March 17, 1885, we filed a patent for all dyestuffs based on tetrazo-bonds of the isomers of tolidine . . . Given the prevailing patent laws, it was necessary to be the first one to file. We could not waste any time. It was possible that AGFA had also found these reactions in the meantime and filed for a patent. For this reason it was standard procedure when one discovered a new reaction to write it down with all its theoretical possibilities in the form of a patent application and mail it the same day for submission to the patent office in Berlin.[41]

This fundamental change of innovation strategy first led to the dye wave (1887–96), in which patents with respect to new dyes (class 22) ranked first in every year. Figure 3 reveals that after a time lag, the invention of new synthetic dyes also accelerated the development of new and complex chemical and mechanical dyeing procedures patented in the technological class dyeing (class 8). This new knowledge then spilled over into the downstream textile industry. The main channel of this knowledge transfer was the customer-consulting service of the German dye producers, who regularly informed textile producers about both new dyes and new dyeing methods.[42] Streb, Wallusch, and Yin have observed a statistical bi-directional Granger causality between German net cloth exports and patents of technological classes dyes and dying, which suggests that during the German Empire the knowledge spillover between chemical and textile firms created an upward circle of endogenous growth.[43] The increasing demand for synthetic dyes by the prospering textile firms initiated further R&D projects by chemical firms that led to new patents and via customer consulting to additional economic benefits of the German textile industry. This process, however, was not infinite, but came to an end when the synthetic dye technology was fully exploited.

Dyestuffs remained the dominating business of the German chemical firms in the nineteenth century.[44] Nevertheless, the research laboratories also started to explore other new technological fields such as inorganic acids, pharmaceuticals, and synthetic fertilizers. The growing importance of these new products was revealed during the chemical wave (1897–1902) when the technological field of chemicals without dyes (class 12) mostly attained rank 1 with regard to the number of high-value patents. As we have already mentioned, this development was fostered considerably by the change in the patent law in 1891.

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[41] Cited after Murmann, *Knowledge*, p. 134.

[42] See Beer, *German dye industry*, p. 91.

[43] See J. Streb, J. Wallusch, and S. Yin, 'Knowledge spill-overs'.

[44] See von Hippel, 'Auf dem Weg zum Weltunternehmen', p. 47.

Surprisingly enough, the wave of electrical engineering (1903–18) was not dominated by the two large companies, Siemens and AEG. In the period between 1901 and 1916, for example, Siemens and AEG only held 10.7 per cent and 7.9 per cent respectively of 2,607 high-value patents in the technological class of electrical engineering (class 21). Our data set enables us to identify other important inventors, for example Felten & Guilleaume AG in Cologne, Robert Bosch in Stuttgart, Hartmann & Braun AG in Frankfurt, and Eisenbahn-Signalbau-Anstalt Max Jüdel & Co. AG in Braunschweig. In Berlin, several innovative firms, such as C. Lorenz Telephon- & Telegrafenwerke AG and Deutsche Telephonwerke GmbH, used the opportunity offered by the new telephone technology to enter the market. These observations suggest that the Schumpeterian hypothesis that firm size is a necessary pre-condition for outstanding innovativeness might have not been generally true during German industrialization.[45] To test this hypothesis, we compare the ranking of the 100 largest German firms of 1907 measured by employment,[46] with their ranking with respect to the number of high-value patents. It turns out that the Spearman's rank correlation coefficient is not positive, but has the negative value –0.242. In the sample of the 100 largest German firms of 1907, the smaller ones were rather the more innovative ones. This finding can be explained by the fact that this sample was dominated by the very large mining, metals, and railway companies such as Bergwerksgesellschaft Hibernia, Röchling'sche Eisen- und Stahlwerke, and Preussisch-Hessische Staatseisenbahn, which could not profit from the technological waves of the second industrial revolution, and had therefore only a very small number of high-value patents.

An interesting facet of the wave of electrical engineering is the patent boom of the technological class of scientific instruments (class 42), which started—similar to the timing of the patent booms in dyes and dyeing—with some time lag to the preceding boom in electrical engineering. Generally, the number of patents in the field of scientific instruments that are needed to develop innovations in most of the other technological fields can be interpreted as an excellent indicator of the innovative potential of an economy. In this respect, the high number of this kind of patents between 1910 and 1918 might indicate that in this period the German industry was well-equipped to produce another generation of high-value patents.

It is widely assumed that German industrialization took place in the transition period between two long Kondratieff cycles, of which the first was dominated by the railway sector, the second by chemicals and electrical

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[45] Following Schumpeter (*Kapitalismus*, p. 135), Galbraith states: 'Thus, in the modern industry shared by a few large firms, size and the rewards accruing to market power combine to ensure that resources for research and technical development will be available . . . The net of all this is that there must be some element of monopoly in an industry if it is to be progressive', Galbraith, *American capitalism*, p. 88.

[46] See Fiedler, '100 größten Unternehmen', pp. 44–8.

engineering.[47] Our analysis confirms this view, and reveals more details about the complexity of the technological development during these cycles. In each of the four technological waves depicted in figure 3, the outburst of innovative activities was not limited to the leading sector, but occurred with some time lag in a couple of other industries that were technologically and economically linked to the original creator of the basic innovations. In this process new knowledge spilled over both from the leading sectors to their customers and suppliers and back from the latter to the former. Firm size was not a necessary precondition for successful patenting activities. This is especially true for the patent booms of dyes and electrical engineering, which were not driven by already long-established firms, but by young companies which then grew because of their above-average innovativeness.

IV

Figure 4 shows that during German industrialization the high-value patents were not more or less uniformly distributed over the different German regions, but were geographically clustered in a broad belt that reached from the districts neighbouring the river Rhine in the West to Greater Berlin and Saxony in the centre.

To control for population density we divided the number of high-value patents by regions' population in the year 1910 for which data are available. As a result of this calculation, some regions in the south-west, such as Neckarkreis and Mannheim, improved their relative innovativeness, while other regions such as Potsdam and Dresden fell behind. Keep in mind that figure 5 is also not a perfect representation for regions' relative innovativeness because their number of residents increased at different growth rates during the period under consideration. However, since both maps show almost the same geographical distribution of patenting activity, we are confident that we can use the absolute number of high-value patents in the following to identify the development of Germany's most innovative regions correctly.

The dominance of the Rhine region and Greater Berlin fit well with Sokoloff's seminal finding that the patenting activities in early nineteenth-century America were concentrated in metropolitan areas and along waterways.[48] Sokoloff explains this geographical clustering of patents mainly by demand factors. He bases his argument on the assumption that the profitability of a patent was the higher the larger the market where the respective innovation could be sold. Because of this correlation, Sokoloff concludes that firms that were either located near highly populated metropolitan areas or could transport their products at low costs along navigable waterways to distant markets had considerably higher incentives to patent than firms in

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[47] See, for example, Freeman, Clark, and Soete, *Unemployment*.

[48] See Sokoloff, 'Inventive activity'.

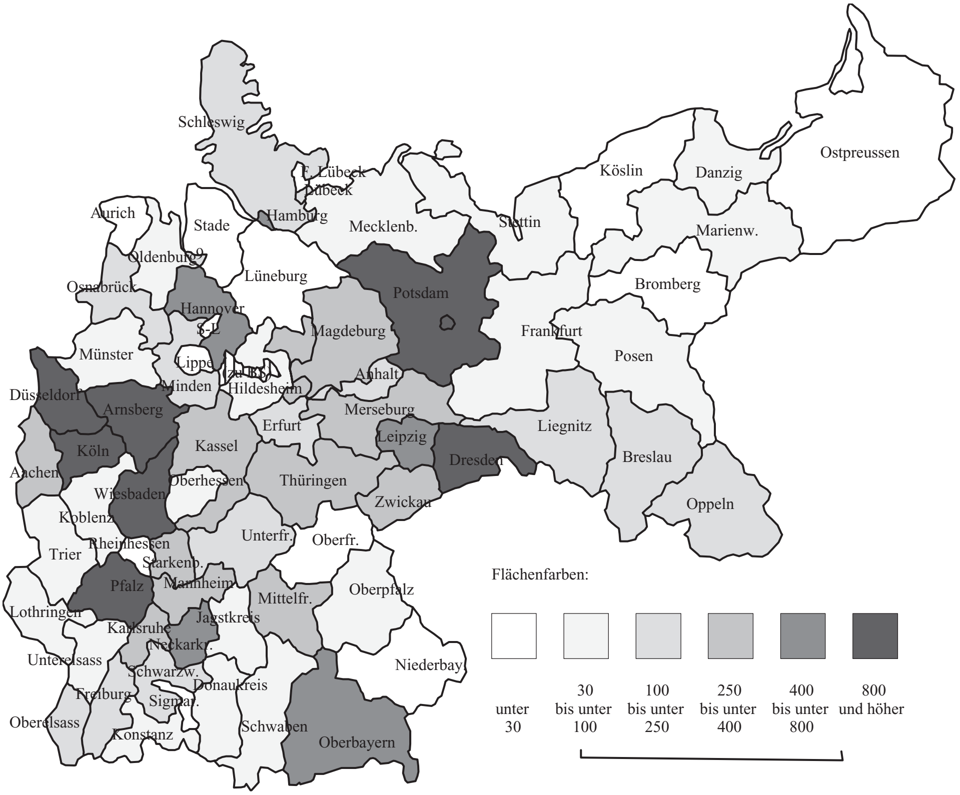

Figure 4. *The geographical distribution of high-value patents 1878–1914*
Source: Baten/Streb database (see text)

more remote areas. As a result, patents were concentrated in the former regions. Demand factors, however, also determine the firms' original choice of location. That is why it is necessary to distinguish clearly between a firm's choice of location and its decision to patent.

Sokoloff is well aware of this problem, and therefore controls for the division of the labour force between agriculture and manufacturing. It turns out that his estimated positive relationship between firms' proximity to navigable waterways and the intensity to patent is robust to the inclusion of this variable, supposed to measure the level of industrial activity in a region. Hence, in Sokoloff's sample, demand factors seem to influence the geographical distribution of patents independently from the original choice of location.

The German case, however, suggests that, because of industries' uneven geographical distribution, the aggregated level of industrial activity might not be adequate to distinguish between the demand effects on the firms' location and patenting decision respectively. Obviously, the broad west-east

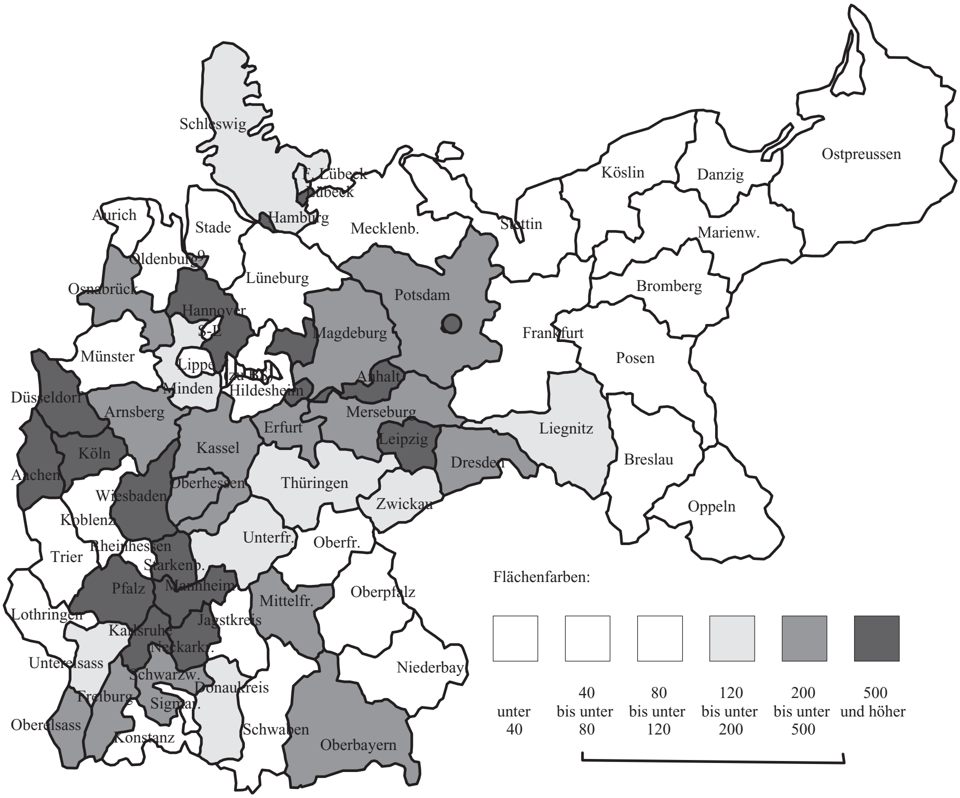

Figure 5. *The geographical distribution of high-value patents 1878–1914 per million residents (population of 1910)*

Source: Baten/Streb database (see text)

strip of German regions with an above-average number of high-value patents was also the favoured location of those industries in which most of the high-value patents originated. Long before the German patent law of 1877 actually came into force, these industries' original choice of location might have been influenced by a variety of factors, such as the expected market volume or the availability of raw materials and intermediate products. Large chemical firms such as BASF or Bayer, for example, preferred to settle at the banks of the river Rhine, which was not only an important navigable waterway, but was also used as a water source and to get rid of effluents. It is therefore conceivable that the great majority of all chemical firms located themselves along waterways. Consequently, waterway areas had an above-average density of chemical firms, and because of this industry's high patenting activity, also had a higher number of patents than regions with a similar industrial activity level that were dominated by industries that patented less than the average. The same argument holds for mechanical and electrical engineering. Firms engaged in the field of mechanical engineering

Table 5. *The most innovative regions during the four waves of technological progress, shares in all high-value patents of the respective wave*

Railway 1877–1886		*Dyes 1887–1896*		*Chemicals 1897–1902*		*Electrical Engineering 1903–1914*	
Region	*Patents (%)*	*Region*	*Patents (%)*	*Region*	*Patents (%)*	*Region*	*Patents (%)*
Berlin	11.7	Berlin	10.7	Berlin	11.7	Berlin	14.2
Düsseldorf	5.6	Düsseldorf	10.7	Düsseldorf	9.3	Düsseldorf	8.9
Dresden	3.8	Wiesbaden	6.2	Wiesbaden	5.4	Wiesbaden	5.6
Leipzig	3.8	Palatinate	3.9	Dresden	2.8	Potsdam	4.2
Wiesbaden	3.3	Dresden	3.0	Palatinate	2.7	Palatinate	2.6
Arnsberg	2.8	Cologne	2.7	Arnsberg	2.3	Arnsberg	2.3
Cologne	2.7	Arnsberg	2.5	Cologne	2.2	Cologne	2.3
Magdeburg	2.6	Leipzig	2.1	Potsdam	2.2	Dresden	2.2
Hamburg	2.2	Chemnitz	2.0	Hamburg	2.1	Leipzig	2.0
Karlsruhe	2.1	Hamburg	1.7	Leipzig	2.1	Neckar	1.8

Source: Baten/Streb database (see text)

were particularly concentrated in the geographical neighbourhood of iron and steel producers, namely in the Greater Ruhr area, and near textile firms, namely in Saxony.[49] Berlin was the centre of German electrical engineering. The fact that the German industries with an apparently above-average propensity to apply for high-value patents were geographically clustered might have led to a quite similar geographical distribution of high-value patents. To check the robustness of the relationship between firms' proximity to metropolitan areas or mass transportation infrastructure and the intensity to patent proposed by Sokoloff, it would therefore be advisable not to control just for the general level of industrial activity, but also for the activity levels of different industries located in the regions under consideration. Using our patent sample, Yin supports Sokoloff's hypothesis by showing that railway density had a statistically significant impact on innovations in the Prussian regions whether patents with respect to chemicals and electrical engineering were excluded or not.[50]

With respect to the share of all high-value patents, the ranking of the most innovative German regions changed during the four waves of technological progress. Table 5 allows us to distinguish regions with continuous, decreasing, and increasing relative innovativeness. Berlin and Düsseldorf kept their leading position during the whole period under consideration, but it is interesting to note that Düsseldorf initially was able to catch up with Berlin

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[49] See Barth, *Entwicklungslinien*, pp. 73–83.

[50] See S. Yin, 'Determinants of innovation in Prussian regions', unpublished paper. Human capital formation, measured by the number of students of technical and commercial schools, also significantly influenced the geographical distribution of high-value patents in Prussia.

during the dye period, and then, fell behind considerably in the period of electrical engineering. Wiesbaden and Palatinate also increased their innovativeness during the dye period, while Potsdam developed its innovative potential mainly during the period of electrical engineering. Dresden and Leipzig, which ranked three and four respectively during the railway period, displayed decreasing relative innovativeness in the following waves of technological progress.

To check whether these changes in the ranking of the most innovative regions could be caused by the transition from one technological wave to the next, we calculated an index of technologically revealed comparative advantage for every technological class, using the following location quotient (LQ), where n denotes the number of patents, subscript i the region, subscript j the technological class, and n_G the total number of high-value patents granted to German patentees in the period between 1877 and 1918:[51]

$$LQ_{ij} = \frac{n_{ij} / n_i}{n_j / n_G} \tag{2}$$

If LQ_{ij} equals 1, patents in technological class j are equally represented in the region i and in Germany. If LQ_{ij} is larger than 1, region i specializes in technological class j.

Table 6 presents the five technological classes with the highest location index for every region named in table 5. In some regions these technological classes formed a cluster of economically and technologically related industries that are named in the last column of table 6. Letters in bold indicate clusters of three or more related industries, normal letters two related industries.

The striking result of this calculation is the fact that most of the regions with continuous innovativeness and all of the regions with increasing innovativeness possessed at least one innovative cluster, while the regions with decreasing innovativeness generally did not. This observation is evidence for the hypothesis that inter-industry knowledge spillovers between geographically concentrated firms were a major source of innovation activities. Berlin specialized in electrical engineering, including signalling and alarm systems, as well as lighting, which perfectly explains its great innovative outcome during the wave of electrical engineering. Wiesbaden and Palatinate had technological revealed comparative advantages in chemicals, and did especially well during the waves of dyes and chemicals. Regions such as Düsseldorf or Potsdam depended heavily on mechanical engineering, but were nevertheless able to keep or even improve their rank under the most

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[51] See Co, 'Geography of innovation', p. 409. See also J. Baten, A. Spadavecchia, J. Streb, and Y. Shuxi, 'Clusters, externalities and innovation: new evidence from German firms, 1890s to 1913', *Working paper* (Tuebingen, 2003).

Table 6. *Technological revealed comparative advantages and innovative cluster*

Region	*Revealed Comparative Advantage* 1	2	3	4	5	*Innovative cluster*
Continuous innovativeness						
Berlin	Electrical engineering (21) 3.2	Signalling (74) 3.1	Lighting (4) 2.4	Printing (15) 2.3	Railway instal-lations (20) 2.0	**Electrical Engineering**
Dusseldorf	Firearms (72) 4.2	Cutting Tools (69) 4.1	Metal sheets (7) 2.7	Iron production (18) 2.5	Dyes (22) 2.4	**Mechanical Engineering**
Wiesbaden	Dyes (22) 4.3	Metallurgical Engineering (40) 3.0	Shoes (71) 2.6	Chemicals (12) 2.5	Ore preparing (1) 2.1	Chemicals + Metallurgical Engineering
Arnsberg	Pumps (59) 11.3	Fuel (10) 9.1	Drying and Roasting (82) 8.9	Tools (87) 6.8	Mining (5) 6.7	**Mining**
Cologne	Rope making (73) 13.7	Internal combustion engines (46) 8.3	Ore preparing (1) 7.7	Harnesses (56) 7.4	Writing Implements (70) 5.6	
Increasing relative innovativeness						
Palatinate	Dyes (22) 5.3	Chemicals (12) 3.8	Dyeing (8) 2.5	Shoes (71) 2.4	Chemical metal processing (48) 1.5	**Chemicals including dyes**
Potsdam	Toys (77) 4.9	Photography (57) 4.8	Vehicle con-struction (63) 2.5	Railway construction (19) 2.2	Burning systems (24) 2.0	**Mechanical Engineering**
Neckar	Internal combustion engines (46) 8.3	Bakery (2) 7.9	Tanning (28) 5.3	Bookbindery (11) 4.7	Cutting tools (69) 3.6	Mechanical engineering

Decreasing relative innovativeness						
Dresden	Glass (32) 11.8	Tobacco (79) 11.5	Control engineering (60) 8.9	Paper processing (54) 4.6	Food stuff (53) 3.5	
Leipzig	Book bindery (11) 13.7	Musical instruments (51) 9.9	Harnesses (56) 7.4	Spinning (76) 3.9	Printing (15) 3.3	Books
Magdeburg	Salt works (62) 30.4	Hat making (41) 12.4	Control engineering (60) 9.0	Harnesses (56) 7.6	Ore preparing (1) 6.6	
Hamburg	Haberdashery (44) 6.7	Ship building (65) 6.4	Sewing (52) 5.3	Food stuff (53) 4.7	Harnesses (56) 4.4	
Karlsruhe	Haberdashery (44) 8.9	Harnesses (56) 8.3	Travelling equipment (33) 6.4	Water-supply (85) 5.8	Explosives (78) 5.2	

Source: Baten/Streb database (see text)

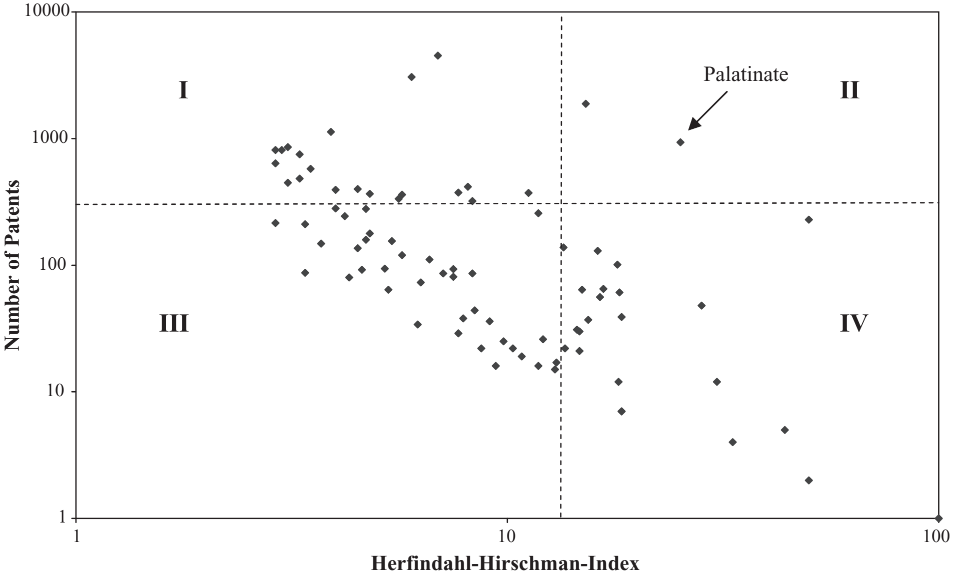

Figure 6. *The technological Herfindahl-Hirschman-Index of the 85 German regions*
Source: Baten/Streb database (see text)

innovative regions after the railway wave had ended. The development of the regions of Cologne, Potsdam, and Neckar suggests that in the early twentieth century, a fifth wave of technological progress with respect to vehicle construction and internal combustion engines started to build up.[52]

The fact that the German regions with a high number of high-value patents often specialized in particular technological fields does not imply that these regions displayed their innovativeness only in a few technological classes. Rather, the opposite was true. As figure 6 shows, the German regions with a high number of high-value patents usually relied on a comparatively high diversity of technological classes, measured by the following version of the Herfindahl-Hirschman-Index (HHI).

$$HHI_i = \sum_{j=1}^{89} \left(\frac{n_{ij}}{n_i} \right)^2 \cdot 100 \qquad (3)$$

Again, *n* denotes the number of high-value patents summed up for the years 1877 to 1918, *i* the region, and *j* the technological class. Here, the Herfindahl-Hirschman-Index will be 100 when a region only patented in one

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[52] In the middle of the 1920s, the classes of internal combustion engines (46) and vehicle construction (63) were ranked sixth and second respectively with respect to the number of patents applied for. See Wernekke, 'Statistik des Reichspatentamtes', p. 414.

technological class, and 1.1 when the patents of a region were equally distributed over the 89 technological classes used by the German patent office.

Every point in this figure represents the combination of the number of high-value patents and the Herfindahl-Hirschman-Index of a particular region. The dotted lines that indicate the mean of the regions' number of high-value patents (302) and the mean of their HHI (13.3) respectively divide the diagram into four sectors. Sector I represents regions with both a high number and a high technological diversity of patents, sector II, regions that had a lot of patents in comparatively few technological classes, sector III, regions with a below-average number of high-value patents in various technological classes, and sector IV, regions that had a small number of patents in only a few technological classes. Almost all regions with an above-average number of high-value patents were located in sector I. The great exception is the Palatinate region, which depended heavily on the patents and knowledge spillovers that originated from the chemical firm BASF.

V

The new data set of 39,343 high-value patents granted by the German patent office between 1877 and 1918 revealed that during German industrialization, technological progress was not a continuous process, but came in at least four different waves. We have been able to identify clearly the railway wave (1877–86), the dye wave (1887–96), the chemical wave (1897–1902), and the wave of electrical engineering (1901–18). In addition, there might have been the beginning of the fifth wave with respect to vehicle construction, not fully disclosed by our data. These successive waves of technological progress had a visible impact on the geographical distribution of high-value patents. Regions such as Berlin, Wiesbaden, or Palatinate, that specialised in the new technologies of the second, third, and fourth waves, showed increasing innovativeness, while other regions such as Dresden and Leipzig, which were not especially engaged in these technological fields, fell behind. We found ample evidence that inter-industry knowledge spillovers between technologically, economically, and geographically related industries were a major source of innovative activities during German industrialization. In a first step, we discovered that most of the parallel patent booms of the successive waves of technological progress occurred in technologically closely related fields. This is, for example, true for steam engines, steam boilers, railway installations, metal processing, and machine parts in the first wave, dyes and dyeing in the second wave, or scientific instruments and electrical engineering in the fourth wave. In a second step, we were able to show that these innovative, technologically related industries were often geographically clustered too. Nearly all regions that kept or improved their above-average innovativeness over time had at least one innovative cluster in the fields of mechanical or electrical engineering or chemicals.

University of Hohenheim and University of Tuebingen

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