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ABSTRACT

Racing against Time in Research: A Study of the 1995 U.S. Patent Law Amendment*

Teamwork in research has been on the rise and so has the size of R&D teams. This paper offers an explanation for increasing team size that we call the "racing against time" hypothesis: With innovation races more competitive globally, R&D firms need to finish research projects as quickly as possible and therefore have an incentive to put together a team with more R&D personnel. We test this hypothesis against a natural experiment that took place in 1995 when the U.S. patent law was amended.

JEL Classification: D23, J23, O32
Keywords: teamwork, team size, R&D, patent, racing against time

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NON-TECHNICAL SUMMARY

Scientific research and innovation is considered as a key driver of economic growth. One stylized fact about modern research is that technological innovation increasingly occurs in teams and the size of research teams has been on the rise. This paper attempts to offer an explanation for increasing team size that we call the "racing against time" hypothesis. With innovation races more competitive globally, R&D firms need to finish research projects as quickly as possible and therefore have an incentive to put together a team with more R&D personnel. We test this hypothesis against a natural experiment that took place in 1995 when the U.S. patent law was amended. The amendment presented an incentive for firms to file quickly inventions that were expected to have a longer monopoly period and firms were thus encouraged to speed up the research on those inventions. We find evidence for a significant increase in team size as a response for this law change.

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I. Introduction

Until half a century ago, scientific discovery was widely considered the realm of individual masterminds such as Einstein and Edison (Lamoreaux and Sokoloff, 2005). As scientific research has since become so complex and scientists have thus had to become more specialized, most significant scientific advancement is now achieved by large and well-funded collaborative teams (Simonton, 2013).

Increasing teamwork in science and research is well documented in numerous studies of various data sources. In the U.S. patent data, the average number of inventors who are listed on a patent, a measure of the size of a research team, rose from 1.70 inventors among patents filed in the first half of 1975 to 2.67 inventors in the second half of 2000 (see Figure 1). The patent data show that 47.1 percent of the U.S. patents filed in 1975 listed multiple inventors while the same was true of 69.8 percent of the U.S. patents filed in 2000.

Patent data from other countries reveal similar trends. The average number of inventors in patents from the European Patent Office (EPO) rose from 1.71 in 1975 to 2.67 in 2000. In patents from the Korean Intellectual Property Office (KIPO), the inventor team size climbed from 1.58 in 1991 to 1.99 in 2005.

Increasing team size is witnessed in academic publication as well. The average number of authors in scientific papers written in top U.S. universities increased by about 50% over the period 1981–1999 (Adams, Black, Clemmons and Stephan, 2005). In the natural sciences, 1.9 authors were listed per paper on average in 1955, compared to 3.5 authors in 2000 (Wuchty, Jones and Uzzi, 2007). The percentage of articles that were co-authored in eight leading economics journals rose from 3% in 1946 to 31% in 1976 (McDowell and Melvin, 1983).

Why are teams getting bigger in innovation and academic research? The literature has offered two major lines of explanation so far. The first pertains to increasing specialization in science and technology. Earlier studies have argued for gains to specialization in teams and pointed out coordination costs as a confining factor for team size (Becker and Murphy, 1992; Bolton and Dewatripont, 1994). From the supply-side perspective, scientists engaged in research specialize in more narrowly defined areas as the existing body of scientific knowledge grows in size. Therefore, it becomes imperative to assemble more scientists with narrower expertise in the conduct of research projects (Jones, 2009).

The second explanation is related to a decline in the cost of collaboration among team members (Adams, Black, Clemmons and Stephan, 2005). The improvement of information and communications technology (ICT) in the past few decades has lowered collaboration costs, which in turn increased the size of research teams within (Forman and van Zeebroeck, 2012) and across organizations such as firms, universities and research laboratories (Arora and Gambardella, 1990).

In this paper, we offer an alternative explanation for rising team size in research. It is well noted in economics and management literature that technology companies are increasingly exposed to time-based competition (Stalk and Hout, 1990). They are squeezed by global market competition to better manage time in innovation, new product development, production and distribution (Griffin, 2002; Lukas, Menon and Bell, 2002; Carbonell and Rodriguez, 2006; Chen, Reilly and Lynn, 2012, Cankurtaran, Langerak and Griffin, 2013).

With innovation races among technology firms ever more competitive due to first-mover advantage, increasing international competition, and stronger IP protection, research firms are under pressure to finish research projects as quickly as possible. Agarwal and Gort (2001) studied how long first mover advantage was preserved for 46 major product innovations and discovered that the average time span between the commercial introduction of a new product and the entry of later competitors was almost 33 years at the turn of the century and has declined to 3.4 years for innovations in 1967–86. Nagaoka, Igami, Walsh and Ijichi (2011) report that the time elapsed from the launch of an R&D project until the submission of a paper becomes shorter if more competitive threat is recognized.

In order to speed up innovation, R&D firms will, in general, increase all types of production inputs for research. The extensive margin of labor is certainly one dimension that can be affected in this endeavor. In other words, firms will put together a team with more R&D personnel to hasten the invention process, which we call the "*racing against time*" hypothesis for rising team size. In this paper, we test this hypothesis against a natural experiment which occurred due to the change in U.S. patent law that took place in 1995.

After 12-year-long negotiations among 123 countries, the Uruguay Round Agreements of the General Agreement on Tariffs and Trade (GATT) were signed on April 15, 1994, which included The Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS). In the U.S., the Uruguay Round Agreements Act was signed into law on December 8, 1994. One key change implemented in this Act was an amendment to the U.S. patent law which was put into effect on June 8, 1995, exactly six months after the Uruguay Round Agreements Act was passed.

Prior to 1995, U.S. patent protection ended 17 years after the patent issue date.[1] The amendment changed the patent term to 20 years after the patent filing date for those patent applications filed after June 8, 1995. A special provision of the new law designed to ease the transition guaranteed that patent applications which were filed between December 8, 1994 and June 7, 1995, but not issued as of June 8, 1995 enjoyed a patent term equal to 17 years post issuance or 20 years post filing, whichever was longer.

This provision presented an incentive for firms to file before June 8, 1995 inventions which were expected to have a longer monopoly period under the old system than under the new system.[2] Firms were thus encouraged to speed up the research on those inventions.[3]

Under the "*racing against time*" hypothesis, we can predict an increase in the team size of inventors for patent applications filed just before June 8, 1995. We empirically investigate this prediction in this paper. Our probe will naturally shed light on issues in team organization, such as how teams are formed and what the factors for team production are. It will also enable us to understand changing nature of the organizational structures used in the development of new technologies.

The structure of the paper is as follows: In section II we describe the data. Section III

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[1] The U.S. Congress established the patent system by the Patent Act of 1790, which instituted a 14-year patent term from issuance. The term was increased to 21 years from patent issuance in 1836 and then decreased to 17 years from patent issuance in 1861.

[2] Continuing patent applications are parts of those that could benefit from the old system. After a patent application is filed, the inventor of the application is entitled to file later one or more continuing applications claiming the priority date of the original or parent patent application. To file a continuing application, a number of conditions must be met, including that the new claims must be fully supported by the subject matter disclosure in the parent application, and the parent application must not yet have been issued into a patent or abandoned (see 35 U.S.C. §119 and §120). Under the old system, the patent protection period for a continuing application starts with its grant date while the period starts with the priority date under the new system. If the priority date is a lot earlier than a continuing application's filing date, the protection term for the application will be quite short under the new system.

[3] Sukhatme and Cramer (2014) showed that the term change encouraged firms to speed up the patent process (also known as patent prosecution) during the patent examination period (especially in pharmaceutical, software and computer industries) since a quicker issuance due to faster prosecution leaves a longer period of patent protection under the new system of a 20-year term after filing.

explains our empirical strategy and Section IV details the model specification for our analysis. In section V we report our empirical results. Concluding remarks are in section VI.

II. Data

2.1 Data Description

We use U.S. patent data for our empirical analysis. The two sources of the data are the "NBER U.S. Patent Citations Data" (Hall et al., 2001) and "NBER Patent Data Project". The former data set covers patent applications filed between 1975 and 1999 while the latter contains applications filed between 1976 and 2006. These data sets include information on assignees (that is, patent right holders), inventor names and addresses, filing and issue dates, claims (itemized description of an invention), technology categories and the like which are collected from the first pages of patents. The data sets also include firm-level variables such as R&D expenditures and the number of employees, which are obtained from the Compustat database using the link between the patent assignees and the Compustat firms completed by the NBER Patent Data Project.

In our analysis, we treat inventors listed on a patent as a research team. A patent-filing agent is legally obligated to list as inventors all researchers who made creative contributions to invention that underlie at least one of the patent's claims.[4] Inventorship on patents is circumscribed rather narrowly by U.S. patent law. For instance, laboratory directorship is sufficient in many disciplines to earn authorship on a scientific publication, but it is insufficient to obtain inventorship on a patent. Also, persons who are technicians or merely took direction from an inventor do not legally qualify as inventors. While in practice the eligibility requirement for inventors may not always be strictly followed, including persons on the patent application who do not satisfy the legal requirement, or excluding persons who do, risks having the patent invalidated (see Crawford and Kokjohn, 2009).[5]

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[4] The U.S. patent law does not require that each inventor contributed to the conception of all claims, or that co-inventors physically worked together. See Manual of Patent Examining Procedure for detailed description of inventorship and its requirements (available online at http://mpep.uspto.gov/).

[5] The increase in the number of inventors per patent could be resulted from changing practices with regards to defining inventorship in patents. However, changes in the practice have been likely in the direction of more strict definition of inventors because there has been a rise in patent infringement litigations. Patent litigation in U.S.

In order to find the shelf life of an invention, we utilize information on patent renewal (or maintenance). Upon the arrival of a new invention, a firm decides whether to file for a patent. When a patent application is filed, a patent can be granted after the examination period (typically two years). Every patent issued for applications filed from December 12, 1980 onwards is subject to the payment of renewal fees, which must be paid to maintain the patent in force.[6] These fees are due at 3½, 7½, and 11½ years from the date on which the patent is granted with the payment window open for six months. At the end of the half-year window, a six-month grace period starts during which a patentee may still pay the renewal fee along with a small surcharge in order to maintain the patent. If the renewal fee has not been paid at the conclusion of the grace period, the patent expires.[7] Data regarding patent renewals and expirations are taken from the Patent Grant Maintenance Fee Events Files from the U.S. Patent and Trademark Office (USPTO).

Patent applicants are legally obligated to disclose and cite any relevant previous inventions on their applications. Patent examiners at the USPTO can add to the application relevant citations omitted by the applicant. Through its citations of previous patents, each patent documents the "prior art" upon which the new invention builds. Citations of a patent by later applications can thus provide a measure of the patent's impact. We use the PTMT (Patent Technology Monitoring Team) database from the USPTO for patent citation information. It includes patent citations for utility patents issued from January 1, 1975 to December 31, 2012.

2.2 Descriptive Analysis

Figure 2 shows the average number of patent applications (that were later granted) per day over a 6-month interval.[8] The number of patents per day was stable before the mid 1980's, but then rose steadily. We find a distinctive surge of application counts in the first half of 1995. This should be due to the special provision presented in the patent law amendment: Before the deadline, firms rushed to file patent applications to take advantage of the extended monopoly period.

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district courts grew in 2015 with 5,830 patent cases filed, a 230% rise from 2009 (2,547 cases).

[6] Patents filed before December 12, 1980 had a full term, that is, 17 years from issuance without payment.

[7] Using records of patents' renewals and expirations, Pakes (1986), Schankerman (1998), Bessen (2008), Deng (2011), Gambardella (2013) have attempted to estimate private pecuniary values and shelf lives of patents under the premise that a patent will not be renewed unless its value exceeds the cost of renewal.

[8] In all figures of this paper, the first half of 1995 comprises days from January 1 until June 7, 1995.

We also find from this figure that there was a dip in the average patent counts immediately after the first half of 1995. This finding suggests that some inventions filed before June 8, 1995 might have been filed after that threshold date if the U.S. patent law had not been amended with the special provision.

Since the provision created a potential benefit exclusively for inventions with a long shelf life, it is likely that inventions with a long lifespan were rushed to be submitted before the deadline. Precisely speaking, it is those inventions that are expected to (i) have patent pendency (length of time between patent application filing and the issue of the patent) longer than 3 years and (ii) have time elapsed from patent filing till expiration (that is, the sum of pendency and patent term) exceeding 20 years.

Besides inventions with a long shelf life that were rushed to be filed before the deadline, there could be another type of intertemporal shift. As firms relocate R&D inputs away from inventions with a short shelf life toward those with a long one, the completion of the former type of inventions will be postponed.

Figure 3 confirms our prediction that inventions with a long lifespan were rushed to be filed. We find that the number of patents which lasted for the full term increased significantly right before the deadline and dipped immediately after it. Interestingly patents with eight or twelve-year terms were also found to rise in number before the deadline despite our prediction of the intertemporal postponement. This may be due to the fact that some inventions that were expected to be renewed to a full patent term *ex ante* may have lost market value rather quickly and been allowed to expire early.

Figure 1 exhibits the number of inventors per patent averaged over a half-year period as a proxy for the size of research team. Consistent with our expectations, we find a big surge in team size in the first half of 1995. This increase may be due to the increase in labor input at the extensive margin as predicted by our "*racing against time*" hypothesis, but could also be due to both types of intertemporal shifts of inventions (rushing inventions with a long shelf life and delaying those with a short life). If inventions with a longer shelf life are more valuable, and more valuable inventions are produced by bigger inventor teams,[9] an increase in team size

[9] The U.S. patent data demonstrate that there is a positive association between team size and patent term. The average number of inventors per patent during period 1981-2000 was 2.18 for patents with a four-year term (those

would naturally result from the intertemporal shifts of inventions. Therefore, in order to isolate the effect on team size under our hypothesis, we need to control for the intertemporal shifts of inventions and the compositional change in patent applications. Our empirical strategy to tackle this issue is explained in the next section.

If inventions with a longer shelf life are more valuable, we can expect that the number of claims per patent is higher in periods just before June 8, 1995 as long as the number of claims is positively associated with the intrinsic value of a patent.[10] Figure 4 shows a surge in the average number of claims per patent in the first half of 1995 amid a steady rise over time.

It has been well documented that there is an increasing backlog of pending patent applications, partly due to a rapid increase in patent filings since the 1980's. Figure 5 consistently shows a rise in patent pendency since at least the late 1980's. The figure also shows a surge in patent pendency in the first half of 1995 and a dip in the following period. This fluctuation in patent pendency can be attributed to a couple of changes noted earlier in this section. First, a surge in the number of patent applications in that period further increased the backlog of pending applications. Second, more valuable applications were filed so that patent examination required more time.

Sukhatme and Cramer (2014) point to another possible reason for a surge in patent pendency. They report that the average pendency time for applications filed in the last month before June 8, 1995 was about 20 days longer than those filed beforehand and that two-thirds of the 20-day delay was due to a longer time taken by applicants when responding to inquiries of the USPTO examiners. This indicates that the special provision in the patent law amendment encouraged R&D firms to file premature patent applications to beat the deadline.

Figure 6 presents the average patent counts and the average team size by technological categories. In both dimensions, we find surges for all categories before the patent law change, but two categories stand out: Drugs & Medical and Chemical. They exhibit the largest surges in patent counts as well as in team size. This finding is consistent with the fact that

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patents not renewed in the 4th year), 2.25 for patents with an eight-year term, 2.30 for patents with a twelve-year term, and 2.33 for patents with a full term.

[10] A patent application contains at least one claim, which states the content of an invention and defines the scope of the protection that is conferred by a patent. A claim can describe a physical entity (apparatus, chemical composition, and the like) or a method (of production or use). A patent owner has the right to exclude others from making, using, or selling those things that are described by the claims (Kim, 2015).

pharmaceutical and chemical patents typically have a long lifespan and can maintain a longer period of monopoly under the old system of patent term (Levin et al., 1987).

III. Empirical Strategy: Estimation of Structural Breaks

If patent filings with varying shelf life were rearranged across periods to take advantage of the special provision in the 1995 patent law amendment, bigger team size before June 8, 1995 can be partly attributed to the compositional change in patent filings. Therefore, in order to test the "*racing against time*" hypothesis, we should check the size of inventor teams not just in the period right before June 8, 1995, but rather over the whole period before and after that date during which the intertemporal shift took place.

How can we identify the time interval over which the intertemporal shift took place? We presume three structural breaks in the time series of patent application counts the dates of which we estimate in our analysis. The time series with the three break dates are illustrated in Figure 7. Because the patent counts seem to increase exponentially in our data since the early 1980's, we take the logarithmic value of patent counts on the y-axis and time periods since 1985 on the x-axis.

Before the first structural break (its break date is denoted by random variable T_1), we assume that the number of patents is growing at a constant rate g_1 which equals to the slope of the straight line between 1985 and T_1. After T_1, there is a surge in patent counts with a constant growth rate g_2 which is bigger than g_1.

The second structural break, denoted by P in Figure 7, takes place when the amendment was implemented on June 8, 1995. Without the intertemporal shift, the number of patent applications would grow after P at a constant rate g_4 which can be either higher or lower than g_1. However, due to the intertemporal shifts, we assume that there is an immediate drop in patent applications after P and then the patent count grows fast to catch up with the trend line. The growth rate during this catch-up process is g_3 and the catch-up is complete at a break date denoted by T_2.

We estimate g_1, g_2, g_3, g_4, T_1 and T_2 by finding those values that minimize the sum of squared residuals (RSS) in the following linear regression (Perron and Zhu, 2005):

$$\ln(PAT_t) = \alpha + \beta_0 \cdot t + \beta_1 \cdot B_{1t} + \beta_2 \cdot B_{2t} + \beta_3 \cdot B_{3t} + \varepsilon_t ,$$

where t denotes time, PAT_t is the number of patent applications per day filed in period t. In this analysis, we use the monthly frequency as our unit of periods.[11] B_{1t}, B_{2t} and B_{3t} are variables for the slope changes defined by

$$B_{1t} = \begin{cases} 0 & \text{if } t < T_1 \text{ or } t \geq P, \\ t - T_1 & \text{if } T_1 \leq t < P, \end{cases}$$

$$B_{2t} = \begin{cases} 0 & \text{if } t < P \text{ or } t \geq T_2, \\ t - T_2 & \text{if } P \leq t < T_2, \end{cases}$$

$$B_{3t} = \begin{cases} 0 & \text{if } t < T_2, \\ t - T_2 & \text{if } t \geq T_2. \end{cases}$$

In this estimation equation, we note that the constant patent growth rates in our model can be estimated as follows: $g_1 = \beta_0$, $g_2 = \beta_0 + \beta_1$, $g_3 = \beta_0 + \beta_2$, $g_4 = \beta_0 + \beta_3$. In our estimation, we include twelve dummies for calendar months since there seems to be systematic monthly fluctuations in patent application counts. For instance, the per-day number of patents filed increases significantly in December every year and decreases in January, which may be due to hurried patent filings at the end of a year.

Our estimation results indicate that T_1 is the end of April 1995 and T_2 is the beginning of August 1995. In other words, the surge before the deadline took place only in the month of May 1995 and patent applications were fewer than the trend line in the months of June and July 1995.

The estimated monthly growth rates of patent applications are: g_1 = .0061943, g_2 = .9351112, g_3 = .0694806, and g_4 = .0098364. Figure 8 shows the log number of patent applications per day in a month. The line in the figure is the estimated line from the regression analysis.

We note that the number of patent applications is increasing faster after 1995: the average growth rate of patent counts rose from 0.62% (before 1995) to 0.98% per month (after

[11] We include patent applications filed on June 1 – 7, 1995 in the month of May when calculating the average number of patents per day by month. In our analysis at the monthly frequency, P is the beginning of June 1995.

1995). This increase may result from more filings of patents with pendency less than 3 years due to patent term extension following the amendment (Abrams, 2009). It is also consistent with the finding in Forman and van Zeebroeck (2012) that lower communication costs due to the universal adoption of the internet since 1995 fostered R&D collaborations and productivities.

In our analysis in the following section, we utilize the finding that the time interval over which the intertemporal shift took place was May-July 1995 in order to control for the compositional changes in patent applications and isolate the effect of the "*racing against time*" hypothesis on team size.

As part of the sensitivity analysis, we also carried out the aforementioned procedure with our data at the weekly frequency. The interval of the intertemporal shift is estimated to cover three weeks before and five weeks after June 8, 1995, which implies the interval starting on May 18 and ending on July 12. We later use this alternative interval in one of the regression specifications.

IV. Empirical Specification

In this section we describe the empirical specification for testing our "*racing against time*" hypothesis. Our dependent variable is the number of inventors appearing on a patent which proxies the size of a research team. The unit of observation for the analysis is a patent. We include all patents applied for by corporations between 1975 and 2006.

The basic specification for our analysis of team size is a Poisson model with firm-level fixed effects. We employ the Poisson model because the dependent variable in our analysis is a nonnegative count variable.

The key regressor in our analysis is a dummy variable for the time interval over which the patent law amendment gave rise to the intertemporal shift of patent applications. Based on the result of the previous section, this variable equals one when a patent is filed in May through July of 1995. We use this variable instead of a dummy variable for patents filed just in May 1995 to eradicate the compositional effect on team size due to intertemporal shifts. If the "*racing against time*" hypothesis is valid, the coefficient associated with this variable should be positive.

The vector of explanatory variables also includes other firm-level and patent-level covariates. To capture the scale effect in research enterprise as well as the maturity of the firm's technology, we include firm-level R&D expenditures in the filing year. For firm-years where R&D expenditure is reported as zero we substitute in the minimum non-zero R&D expenditure in the data and include a dummy variable that is equal to one for such firm-years. This allows us to take the natural logarithm of R&D without dropping firm-years from the analysis.

We also include employment as a proxy for firm size. Larger firms can enjoy economies of scale in patent production due to the fixed cost of maintaining a legal department (Hall and Ziedonis, 2001), or firms in more technology-oriented sectors may have fewer employees given the size of R&D enterprise.

It is well noted in the literature that inter-firm mobility of researchers has been on the rise and high-tech firms are aggressively soliciting technologies developed by competing firms through mobility (Kim and Marschke, 2005). Rising mobility can affect R&D team size adversely because more leaving researchers mean greater appropriation cost. On the other hand, in response to leaving researchers, R&D firms have an incentive to "compartmentalize" their research projects and spread the research tasks around greater numbers of researchers so that single researchers lack sufficient information to recreate the project on their own (Kim and Marschke, 2017). Our analysis employs variations in enforceability of non-compete covenants across states and years as a proxy for labor mobility (Bishara, 2011; Garmaise, 2011; Samila and Sorenson, 2011) to identify the effect of labor mobility on team formation in R&D.

A non-compete covenant is a promise by a worker not to work with a direct competitor for a fixed period of time following the end of employment. Non-compete covenants are commonly incorporated into employment contracts of researchers. Some states enforce non-compete covenants, but the others are reluctant to enforce them because of the restrictions they place on the worker's ability to secure employment. In states and years where non-compete agreements are enforced, the risk that a researcher will appropriate valuable intellectual property is lower and labor mobility will thus be lower. Following Marx et al. (2009), we use the method in Malsberger (1996) to identify the states and the years that restrict non-compete enforcement (see Appendix A for the list).

Each claim documented on a patent describes one facet of the contents of an invention (see footnote 10). The number of claims can hence be used as a proxy for the value of the patent or as a measure of its scope or width (Lanjouw and Schankerman, 2004). This variable can influence team size if more valuable or extensive patents require more R&D personnel.

Based on the evidence from Trajtenberg (1990) that citations received (or forward citations) reflect the economic value of a patent, we include as a regressor the number of citations that the patent receives in the five years that follow the grant date. Ideally, we want to count all citations that a patent receives in its whole lifespan. However, due a data-censoring problem, we choose a cut-off point at 5 years after a patent's issuance.

Since the dependent variable in our estimation is time-trended, we add time trend variable (*T*) to the vector of explanatory variables. Variable *T* is the number of months elapsed since January 1975. In order to account for other possible missing trended variables more precisely, variable *T* is entered in high-order polynomial forms up to quintic form.

Our empirical analysis of team size also includes dummy variables for six patent technological categories (Chemical, Computers & Communications, Drugs & Medical, Electrical & Electronic, Mechanical, and Others. See Appendix B for the list of subcategories) and for twelve calendar months.

All explanatory variables are in logarithmic form except for indicator variables. Note that in the Poisson specification the estimated coefficients associated with the regressors in logarithmic form have an elasticity interpretation. Table 1 reports the definitions and summary statistics of the variables that are used in the regression analysis.

V. Regression Results

Table 2 shows the results from the analysis of team size. In the first column, we report the result from the model only with our key regressor, dummy variable for patents filed in May through July of 1995, included. In the second model which is our benchmark case, we include the basic set of regressors described in the previous section.

In models 1 and 2, the dummy variable for whether a patent application was filed in May through July of 1995 is shown to exert a statistically significant and positive effect on team size. Those patent applications that were rushed to be filed to beat the deadline have bigger research teams, which supports the "*racing against time*" hypothesis. A bigger research team is evident even after the intertemporal shift of inventions are taken into account.

It is only those inventions with a long expected lifespan that can take advantage of the special provision in the 1995 patent law amendment. Therefore, under the "*racing against time*" hypothesis, team size is expected to get bigger just for inventions with a long shelf life. We check the validity of this prediction in model 3. In this model the dummy variable for patents filed in May through July 1995 is interacted with four dummy variables for patents that each had a four-year, eight-year, twelve-year, and full patent term, respectively.

The result from model 3 indicates that inventions that were maintained in force for a full term had a biggest increase in team size during the period of May - July 1995 among all types of inventions with different patent terms. For inventions with a four-year patent term, there is no significant increase in team size at all.

We did not consider model 3 as a benchmark case because inventions affected by the special provision in the amendment are those which are expected *ex ante* to have a long shelf life, but our patent term data pertain to *ex post* outcomes. As noted in section 2.2, a patent that was expected to have a long shelf life and thus affected by the provision may turn out to lose its market value quicker than expected, to which an increase in team size among patents with an eight-year or twelve-year term can be attributed.

Based on the estimated coefficients in models 1 and 2, we find that team size during the time period of our interest is bigger by 4.77% (=exp(.04658)) and 4.80% (=exp(.04690)), respectively. The coefficient estimate in model 3 indicates that the team size for patents with full terms is bigger by 5.76% (=exp(.05603)) during that period.

We find in Table 2 a significantly positive relationship between the size of the firm's R&D enterprise and the size of its teams. If firms with larger R&D enterprise produce more valuable inventions in general and valuable inventions require more research personnel, we would expect bigger team size for those firms, given other control variables constant. Our fining is consistent with this prediction.

Table 2 also shows that the larger the firm in terms of employment with R&D

expenditures held constant, the smaller its research team size. Bigger firms with the size of R&D expenditures held constant may operate in a less technology-oriented sector, which can account for smaller team size.

The dummy variable for whether the first inventor on a patent resides in a state that enforces non-compete clauses is shown to have a statistically significant and positive coefficient. This implies that all else equal, research teams in a state where non-compete clauses are enforced are bigger. The enforcement of non-compete clauses can reduce the gain from moving to a competitor by transferring knowledge, and therefore inventor-employees in states where non-compete clauses are enforced are less likely to move. Therefore, our result indicates that higher labor mobility results in a reduction in team size due to greater appropriation cost.

We find that a patent with more claims has a significantly more inventors involved. This finding is consistent with the conjecture that the number of claims documented on a patent captures the value or the scope of an invention. The number of forward citations, another measure of a patent value, is shown in this table to have a significantly positive association with R&D team size as well.

Time trend variable in high-order polynomial forms up to quintic form is shown to exert a statistically significant effect on team size. We find that team size is generally bigger for inventions in such categories as Chemical and Drugs & Medical while it is smaller in Computers & Communications, Electrical & Electronic and Mechanical. Team size is found to be bigger for patents filed in February, April and May but smaller in December and January (not reported to save space).

We noted earlier that the special provision in the 1995 amendment grants extended monopoly power only to those inventions that satisfy the two conditions: (i) patent pendency is expected at the time of filing to be longer than 3 years and (ii) time elapsed from patent filing until expiration (that is, the sum of pendency and patent term) is expected to exceed 20 years. Since those inventions cannot be identified in our data, we use an alternative sample of patents in Table 3 with the assumption that an invention's shelf life is materialized as expected. This sample includes patents that had the recorded pendency longer than 3 years and were renewed to full patent terms.[12]

In models 1 and 2 of Table 3, the dummy variable for patents filed in May 1995 is shown to have a significant and positive effect on team size. This confirms again our finding in Table 2 that those patent applications which were rushed to beat the deadline have bigger research teams, and therefore supports the "*racing against time*" hypothesis.

The magnitude of the effect on team size is more pronounced in Table 3 than in the previous table. The result in model 2 reports that the size of research team for patents filed in May 1995 is bigger by 10.2% (=exp(.09694)), which is twice larger than in model 2 of Table 2. The other regressors in Table 3 have quantitatively similar effects on team size as in Table 2.

As part of the robustness checks, we use an alternative time interval of the intertemporal shift from May 18 until July 12, which is estimated from the procedure in Section III with the data at the weekly frequency instead of the monthly frequency. In model 1 of Table 4, the dummy variable for this alternative period is also shown to have a significantly positive effect on team size.

It is well recognized in the economics literature on innovation that firms in such industries as pharmaceuticals and chemicals rely heavily on patents to recoup their R&D investments and tend to maintain patents in force for full terms (Levin, Klevorick, Nelson and Winter, 1987). In models 2 and 3 of Table 4, we include patents from the pharmaceutical industry and the chemical industry, respectively. Those patents in the two sectors are found to have a big increase in team size during the period of our interest.

VI. Concluding remarks

The last half century has witnessed a steady rise in teamwork in science and research as well as a persistent increase in the size of R&D teams. Rising teamwork in science and research is evident from various data sources that include patents and academic publications.

There have been two major explanations put forward in the literature for rising

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[12] The sample includes patents filed on or after December 12, 1980 on which date the patent renewal system was first implemented.

teamwork: increasing specialization in research (e.g., Jones, 2009) and falling collaboration cost (e.g., Adams, Black, Clemmons and Stephan, 2005). In this paper we propose an alternative hypothesis.

In fast races of innovation, it is imperative for a firm to innovate first due to the tournament aspect of research that a winner takes all. To speed up the research process or increase the quantity and the quality of research output, firms must increase inputs of various types and they may respond with the extensive margin of labor, that is, more R&D personnel per research project. According to this story which we call the "racing against time" hypothesis, rising trend in R&D team size can be attributed to growing competitive pressure to innovate fast.

We test this hypothesis against a natural experiment that took place in 1995 when the U.S. patent law was amended. A special provision in the amendment provided an incentive for innovating firms to hurry up research to beat the deadline for patent filing. To be consistent with the hypothesis, we find that firms filed more patents right before the deadline and those patents listed more inventors even after controlling for possible intertemporal shift of inventions with various lengths of shelf life.

A caveat is in order with regard to our finding. The estimated increase in team size during the period of our interest may be underestimated. The reaction of innovating firms to the special provision was a short-run response and firms might be reluctant to temporarily hire new researcher-employees. On the contrary, intensifying competition in the market may induce long-run responses from research firms, and thus a large increase in team size may ensue.

While the empirical results generally support our hypothesis, we have left a number of issues unaddressed. First, this paper did not investigate a direct association between time-based competition and rising team size. We may need detailed firm-level data to estimate the magnitude of the impact of time-based competition on rising trend in team size.[13]

Second, we did not bring the three hypotheses for rising team size into a horse race in this paper. Against our "*racing against time*" hypothesis, we can formulate discriminating

[13] Time-based competition can be measured by, for example, the time length of a product cycle or the extent of market competition in an industry. It will be, however, extremely challenging to categorize products and markets or quantify market competitiveness.

implications of the other two hypotheses. In the story of increasing specialization, rising trend of team size should be accompanied by team members with more diverse, specialized expertise. On the other hand, in our hypothesis, more team members are assembled even with the same set of skills and therefore we witness stronger collaboration of equals. If falling collaboration cost is a key driving force behind rising team size, its effect should be more pronounced *across* firms instead of *within* a firm because communication cost within the boundary of a firm should be more readily minimized. In other words, inventions from inter-institutional collaboration are expected to have a faster rise in team size according to the "falling collaboration cost" hypothesis. On the other hand, our "*racing against time*" hypothesis predicts a faster rise in team size among inventions by researchers within a firm. We leave these issues to future work.

Appendix

A. List of states which had specific legislation restricting enforcement of non-compete covenants (all sample years unless noted in the parentheses)

Alaska, California, Connecticut, Michigan (-March 1985) Minnesota, Montana, North Dakoda, Nevada, Oklahoma, Washington, and West Virginia

B. Patent technology categories (NBER Patent Citations Data, Hall, Jaffe, and Trajtenberg, 2005)

Category 1: Chemical (Subcategory 11: Agriculture, Food, Textiles; 12: Coating; 13: Gas; 14: Organic Compounds; 15: Resins; 19: Miscellaneous-chemical)

Category 2: Computer & Communication (Subcategory 21: Communications; 22: Computer Hardware & Software; 23: Computer Peripherals; 24: Information Storage)

Category 3 Drug & Medical (Subcategory 31: Drugs; 32: Surgery & Medical Instruments; 33: Biotechnology; 39: Miscellaneous-Drug & Medical)

Category 4: Electrical & Electronic (Subcategory 41: Electrical Device; 42: Electrical Lighting; 43: Measuring & Testing; 44: Nuclear & X-rays; 45: Power Systems; 46: Semiconductor Devices; 49: Miscellaneous-Electronic)

Category 5: Mechanical (Subcategory 51: Materials Processing & Handling; 52: Metal Working; 53: Motors, Engines & Parts; 54: Optics; 55: Transportation; 59: Miscellaneous-Mechanical)

Category 6: Others (Subcategory 61: Agriculture, Husbandry, Food; 62: Amusement Devices; 63: Apparel & Textile; 64: Earth Working & Wells; 65: Furniture, House Fixtures; 66: Heating; 67: Pipes & Joints; 68: Receptacles; 69: Miscellaneous-Others)

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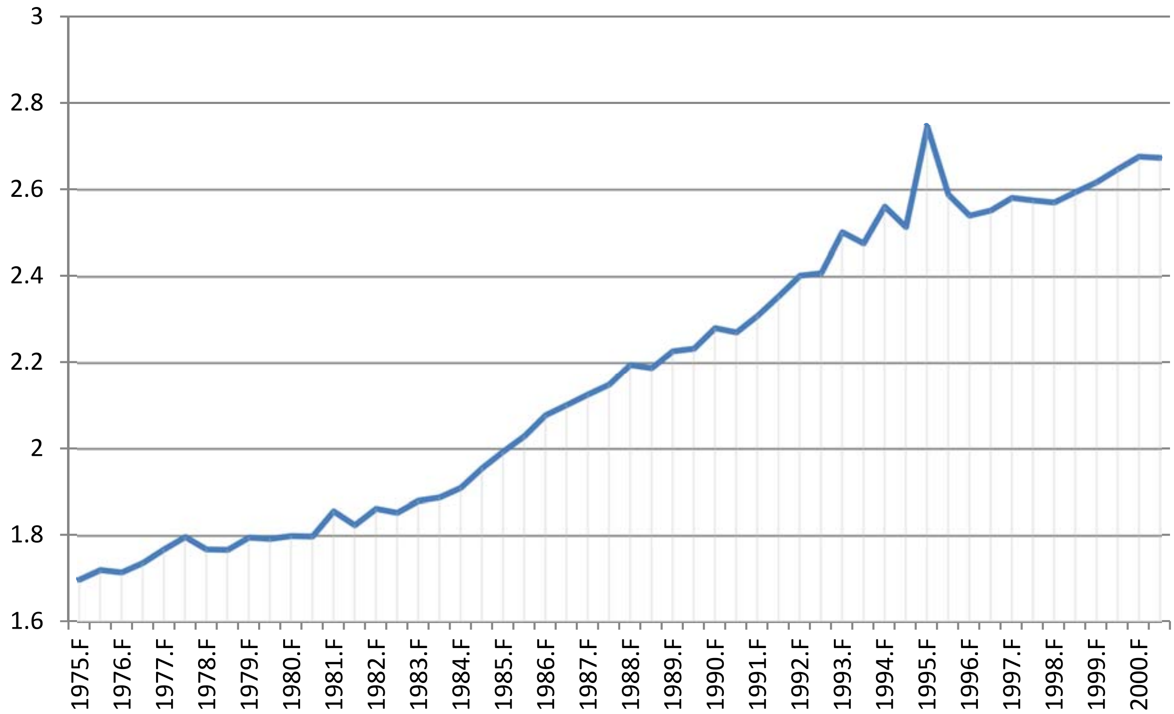
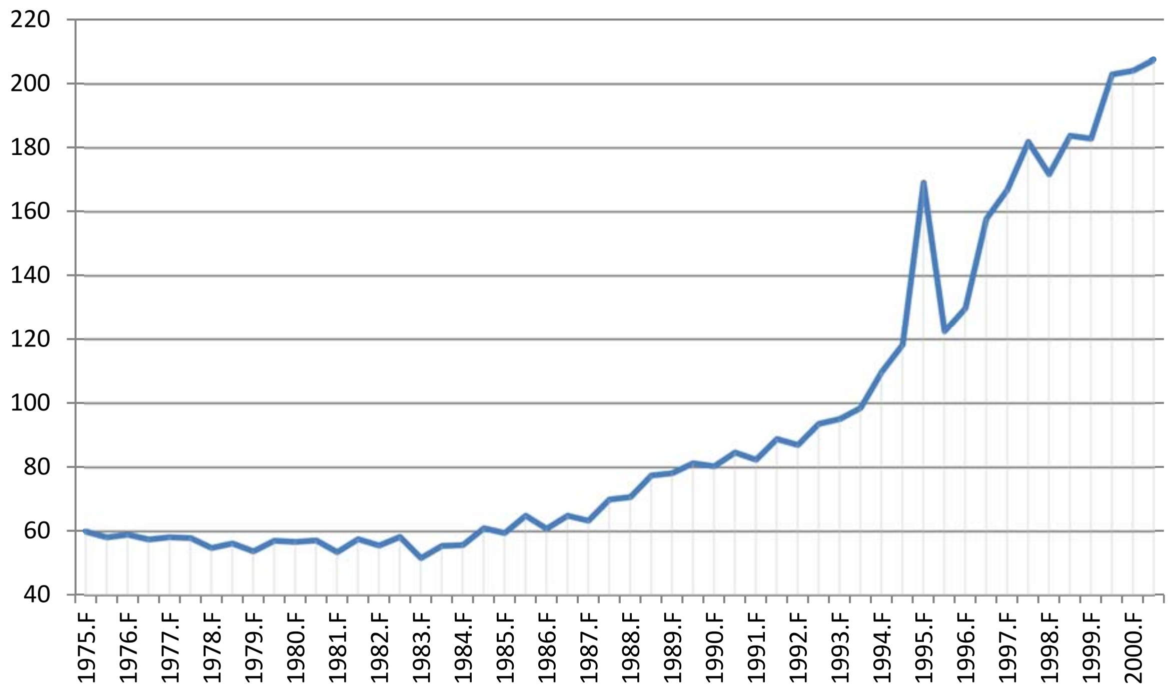
Figure 1. Average Number of Inventors per Patent in a Half Year



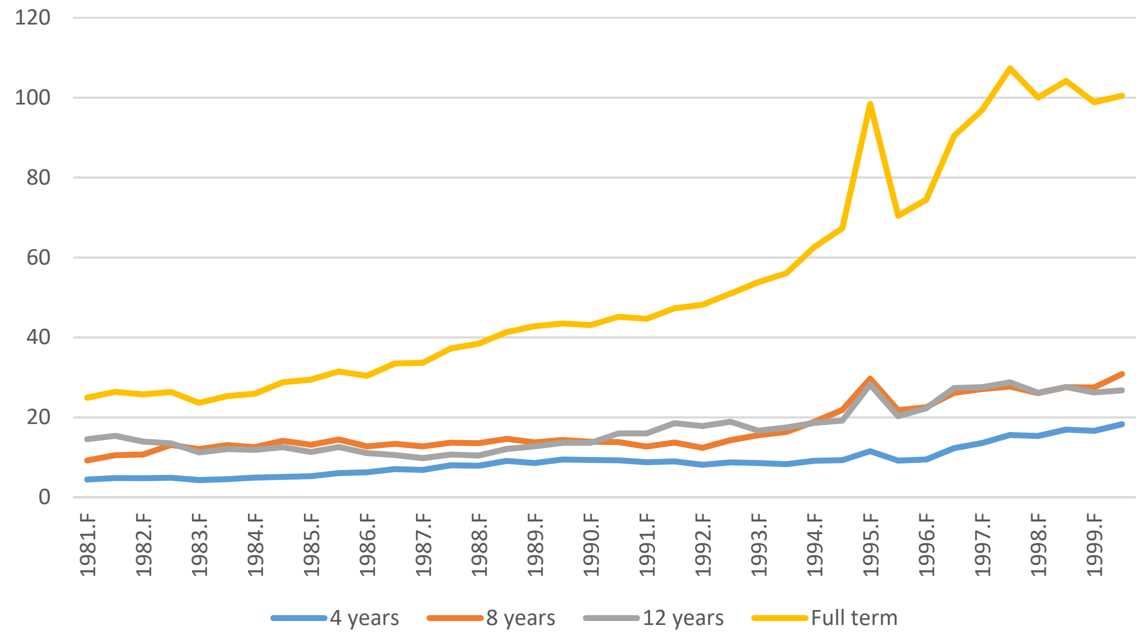
Note: Data from the NBER Patent Data Project. Application year on the horizontal axis where 1975.F denotes the first half of year 1975.

Figure 2. Average Number of Patents Filed per Day in a Half Year



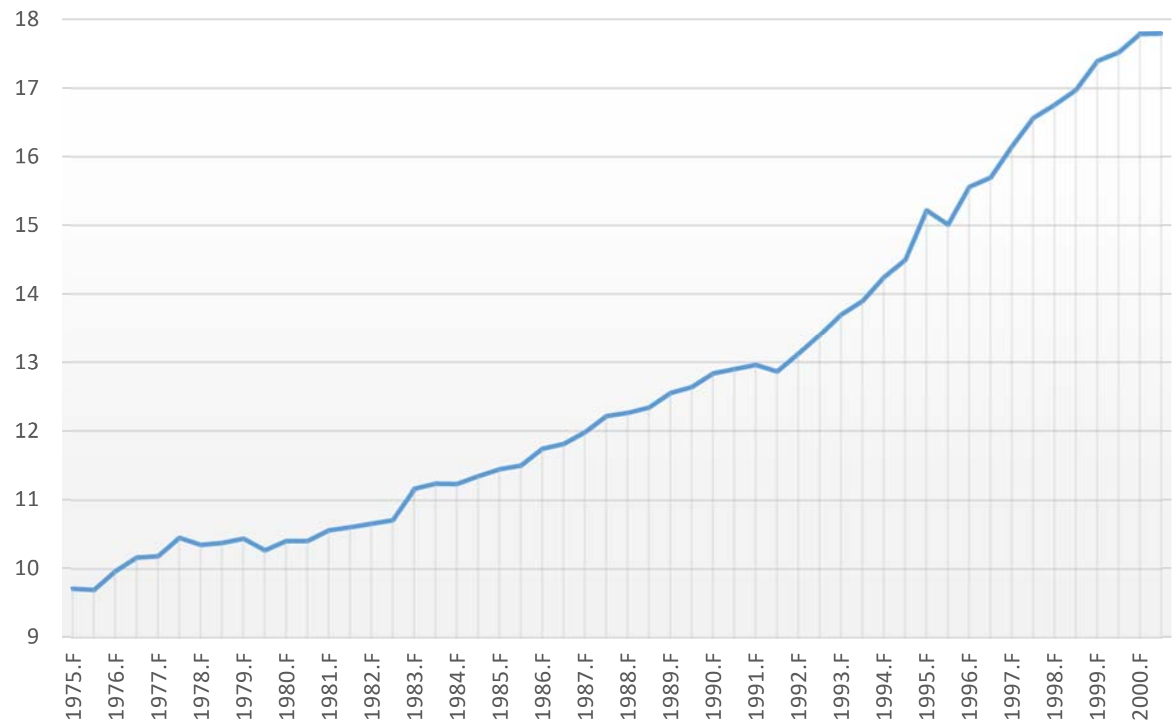
Note: Data from the NBER Patent Data Project. Application date on the horizontal axis where 1975.F denotes the first half of 1975.

Figure 3. Average Number of Patents Filed per Day in a Half Year by Term Length



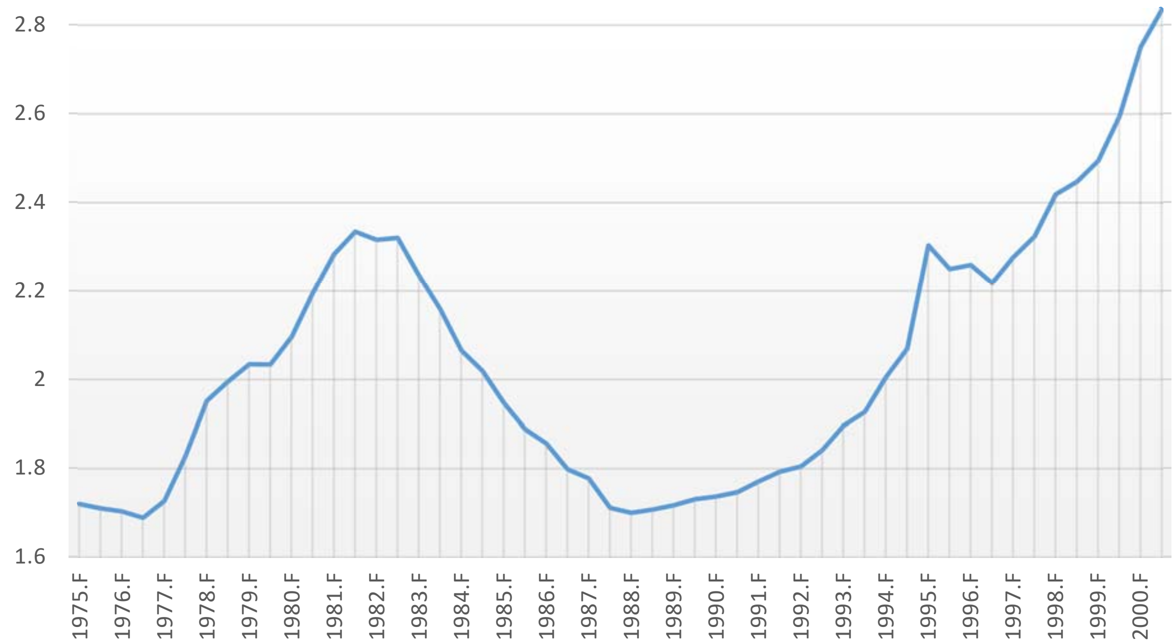
Note: Data from the NBER Patent Data Project. Application year on the horizontal axis where 1975.F denotes the first half of year 1975. The blue line for “4 years” represents patents which were not renewed in their fourth year.

Figure 4. Average Number of Claims per Patent in a Half Year



Note: Data from the NBER Patent Data Project. Application year on the horizontal axis where 1975.F denotes the first half of year 1975.

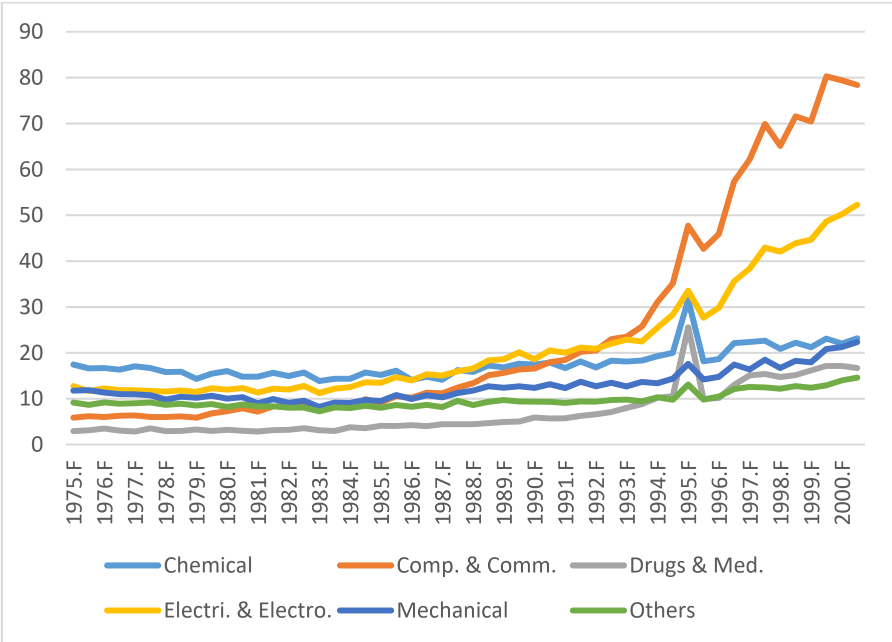
Figure 5. Average Patent Pendency



Note: Data from the NBER Patent Data Project. Application year on the horizontal axis where 1975.F denotes the first half of year 1975. Patent pendency is the length of time between patent application filing and the issue of the patent.

Figure 6. Patent Counts and Team Size by Technological Categories

A. Average Number of Patents Filed per Day in a Half Year



B. Average Number of Inventors per Patent in a Half Year

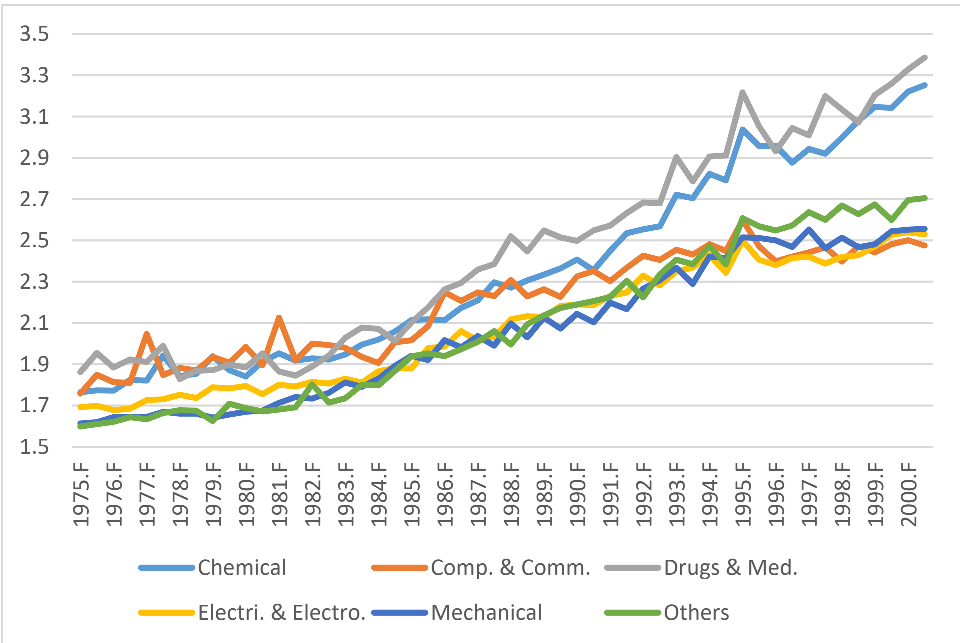


Figure 7. Finding Breaks in the Time Series of Patent Counts

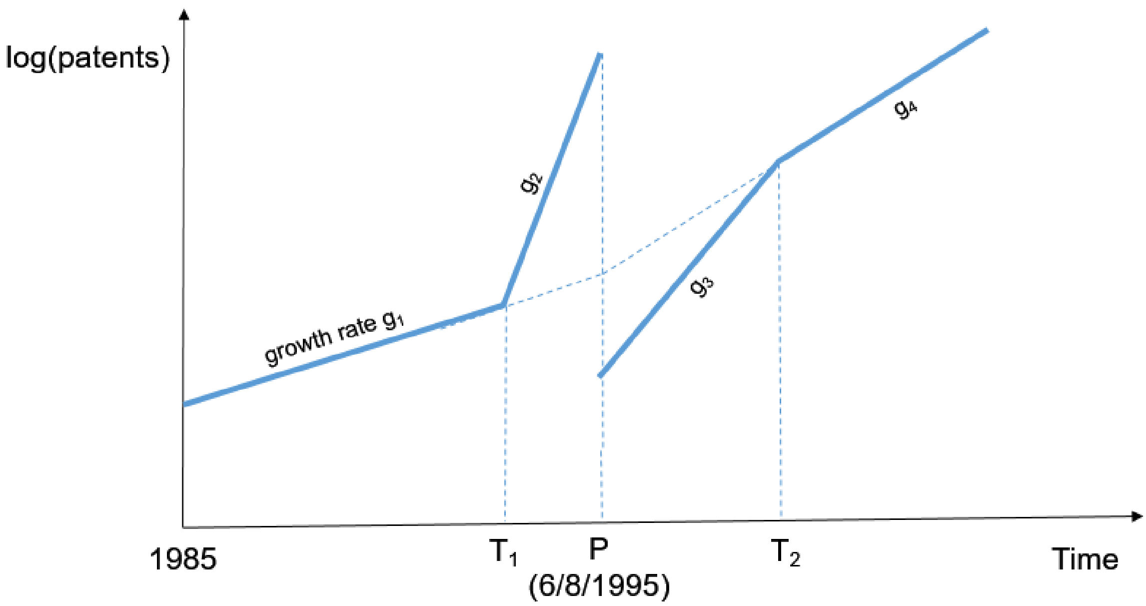


Figure 8. Structural Breaks in Patent Counts

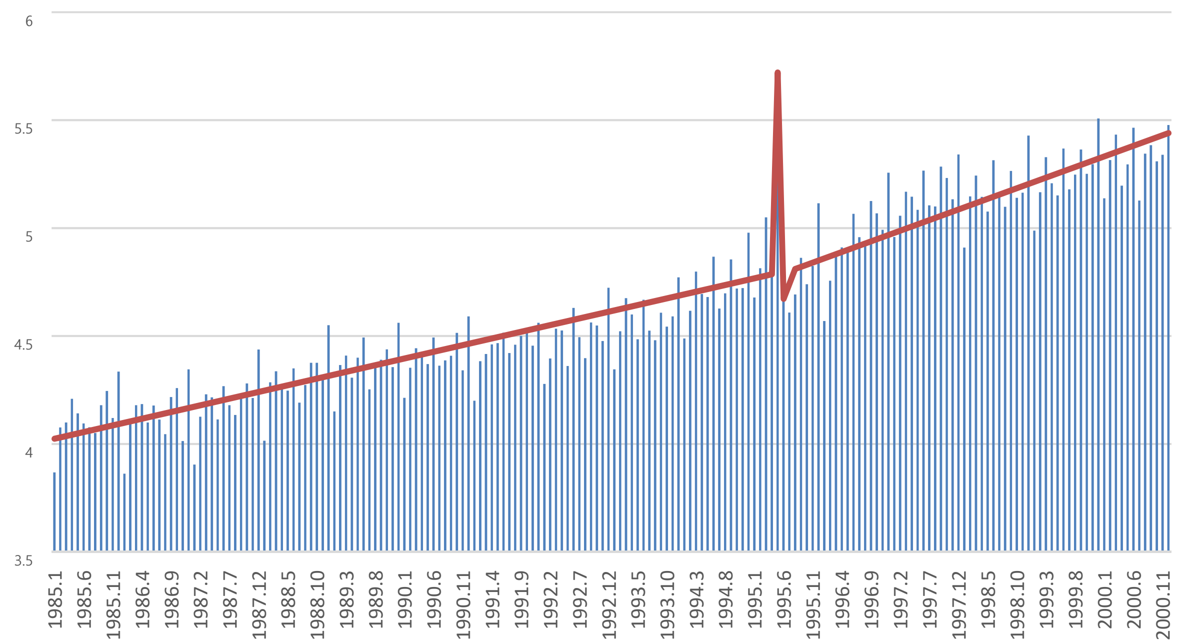


Table 1. Variables Used in the Empirical Analysis

Variable	Description	Mean [Std. Dev.]	Min	Max
Team size	Number of inventors appearing on a patent	2.2992 [1.568]	1	51
May-July 95	= 1 if a patent is filed between May 1 and July 31, 1995 (three-month period)	.0157 [.124]	0	1
May 95	= 1 if a patent is filed during the month of May in 1995	.0051 [.071]	0	1
May 18 – July 12, 95	= 1 if a patent is filed between May 18 and July 12, 1995 (eight-week period)	.0 [.]	0	1
R&D	Firm's annual R&D expenditures in real terms (million $ 1982-84)	717.84 [992.5]	0	6623
Employees	Number of employees (100s)	102.00 [144.9]	.001	1700
Noncompete	= 1 if the first inventor resides in a state that enforces non-compete clauses in a given year	0.7093 [.454]	0	1
Claims	Number of claims on a patent	16.741 [13.55]	1	706
Forward citations	Number of citations a patent received in 5 years following its granting	6.4721 [10.93]	0	484

Note: Summary statistics reported are based on the pooled sample of 652,788 observations (used in model 2 of Table 2).

Table 2. Determinants of R&D Team Size

Dependent variable: Team size — Poisson model w/ firm-level fixed effects

Regressor	Model 1	Model 2	Model 3
May-July 95	0.04658***	0.04690***	
	9.33	7.21	
May-July 95*4-year term			0.00551
			0.22
May-July 95*8-year term			0.04231***
			2.70
May-July 95*12-year term			0.03564**
			2.22
May-July 95*Full term			0.05603***
			6.98
Log R&D		0.01145***	0.01279***
		4.17	4.16
Zero R&D dummy		0.29174***	0.31015***
		3.95	3.74
Log Employees		-0.00702**	-0.00833**
		-2.02	-2.11
Noncompete		0.02111***	0.02174***
		8.69	8.45
Log Claims		0.04508***	0.04756***
		39.48	39.08
Log Forward citations		0.00730***	0.00839***
		28.75	29.65
T, T^2, T^3, T^4, T^5	Yes	Yes	Yes
Dummies for:			
Patent tech. categories	Yes	Yes	Yes
Calendar months	Yes	Yes	Yes
Log likelihood	-1852665.6	-1069613.9	-944413.52
Observations	1,095,891	652,788	561,452

Notes: *** significant at 1%; ** significant at 5%; * significant at 10%. For each regressor, its estimated coefficient and the z value are reported in the first and the second row, respectively.

1. Models 1 and 2 include patents filed for between 1975 and 2006, inclusive. In model 3, we include only those patents filed on or after December 12, 1980 on which date the patent renewal system was first implemented.

2. Patent technology categories: (1) Chemical, (2) Computers & Communications, (3) Drugs & Medical, (4) Electrical & Electronic, (5) Mechanical, and (6) Others. (Source: NBER Patent data)

Table 3. Determinants of R&D Team Size: Patents with a Full Term

Dependent variable: Team size — Poisson model w/ firm-level fixed effects

Regressor	Model 1	Model 2
May 95	0.07077***	0.09694***
	2.91	3.24
Log R&D		-0.00583
		-0.48
Zero R&D dummy		0.32264
		1.17
Log Employees		0.01889
		1.24
Noncompete		0.01209
		1.30
Log Claims		0.05191***
		11.76
Log Forward citations		0.01217***
		12.26
T, T^2, T^3, T^4, T^5	Yes	Yes
Dummies for:		
Patent tech. categories	Yes	Yes
Calendar months	Yes	Yes
Log likelihood	-110585.75	-66488.065
Observations	63,079	39,174

Notes: *** significant at 1%; ** significant at 5%; * significant at 10%. For each regressor, its estimated coefficient and the z value are reported in the first and the second row, respectively.
1. We include only those patents that were renewed to full patent term with pendency longer than 3 years.
2. All models include patents filed on or after December 12, 1980 on which date the patent renewal system was first implemented.
3. Patent technology categories: see note in Table 2.

Table 4. Additional Analysis of Team Size

Dependent variable: Team size — Poisson model w/ firm-level fixed effects

Regressor	Model 1 Alternative period	Model 2 Drugs	Model 3 Chemicals
May-July 95		0.05309***	0.05814***
		2.90	3.99
May 18 – July 12, 95	0.04714***		
	6.21		
Log R&D	0.01144***	0.00484	0.03370***
	4.16	0.42	4.85
Zero R&D dummy	0.29246***	0.34844	0.37410**
	3.96	1.36	2.35
Log Employees	-0.00700**	-0.00592	-0.02984***
	-2.02	-0.45	-3.44
Noncompete	0.02112***	0.03361***	0.03342***
	8.70	2.69	4.85
Log Claims	0.04506***	0.05623***	0.04354***
	39.46	13.33	17.17
Log Forward citations	0.00729***	0.00277***	0.00498***
	28.74	3.18	9.89
T, T^2, T^3, T^4, T^5	Yes	Yes	Yes
Dummies for:			
Patent tech. categories	Yes	-	-
Calendar months	Yes	Yes	Yes
Log likelihood	-1069620.5	-56011.663	-187859.83
Observations	652,788	31,107	117,509

Notes: *** significant at 1%; ** significant at 5%; * significant at 10%. Coefficient and z-value reported in the first and second row, respectively

1. All models include patents filed for between 1975 and 2006, inclusive.
2. Patent technology categories: see note in Table 2.
3. Model 2 includes patents with the technology subcategory of 31 (Drugs) while model 3 includes those with the technology subcategories of 12 (Coating chemical), 13 (Gas chemical), 14 (Organic compounds), 15 (Resins chemical), 19 (Miscellaneous chemical). (Source: NBER Patent data)