COMPARATIVE PRODUCTIVITY OF INVENTORS IN EMERGING RESEARCH ORGANIZATIONS:

Some Evidence from the U.S. Petroleum Industry

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Perhaps the most widely tested implication of Schumpeterian competition is firm-size difference in inventive activity. Literature on the subject emerged in the sixties and the seventies with a somewhat conflicting overview — large firms in general undertake more R&D, but independent inventors and small firms allegedly contributed much to major technical advances.[1] This paper offers some new evidence on this issue by studying the productivities of inventors in large versus small research organizations. Our approach differs from conventional analyses in that we explicitly recognize the endogenous nature of research organization, i.e., we view research organization as a set of contractual arrangements voluntarily entered into by otherwise independent inventors. This is to be distinguished from the conventional analyses in which firm size is treated as an exogeneous institutional constraint, with heavy emphasis on large firms' inertia and communication problems.[2]

The second unique feature of the approach used in this study is that our basic unit of analysis is an inventor (rather than a firm or an invention). Inventors are viewed as maximizing individuals with differing abilities, who select research facilities and environments at perfectly elastic prices.[3] We summarize the productivity of an inventor in terms of his career performance on patent record, and we examine its interaction with his research environments.

The model constructed in the paper will be utilized to answer the following questions: (i) Does quantitative career patent performance record, in spite of its stochastic nature and heterogeneity, reflect rational maximizing behaviors of inventors in any consistent way? (ii) Do superior inventors (by patent performance standards) tend to associate themselves with large research organizations? If so, is that because of these organizations' better research and legal facilities for patents? In other words, is the observed relative superiority the result of differences in propensity to patent among research organizations? (iii) Does the ability to cooperate in team work a characteristic highly valued by large research organizations? More generally, does the notion of joint production, which is crucial in the general theory of the firm, equally apply in the case of innovation?

Section I gives the background material for the industry we are examining. We demonstrate how the career patent performance records of inventors in this industry can be systematically analyzed. It will be shown that the summary statistics based on such records, although subject to wide variation in terms of value and content, do behave consistently, and that a set of meaningful issues concerning the economic behavior of inventors can be examined by utilizing these summary statistics. Section II constructs a theoretical model describing the maximizing behavior of an inventor. The model demonstrates how the summary statistics in Section I may enter into an inventor's gain and cost evaluations. Section III examines how inventors with various characteristics choose their research environments. It is found that superior inventors (according to the ability measure in Section II) are more likely to be in large research organizations. Furthermore, their relative superiority is not resulting from the large organization's propensity to patent. In fact, the data demonstrates that the propensity to patent is lower in large than small organizations — a result that is consistent with earlier findings on the issue.[4] Finally, inventors in large organizations are just as likely to cooperate with other inventors than those in small organizations. Thus, the reason for bigness should be found on other grounds.

I. Enormous structural and technical changes happened in the U.S. petroleum industry early in the twentieth century. Productivity and average firm sizes increased drastically, and there were intense competition on alternative refining techniques of petroleum cracking. These technical changes have been well documented,[5] and the contractual arrangements between competing firms have been expertly analyzed in the literature.[6] We propose to analyze technical changes in the petroleum industry from a different perspective: Our main emphasis is in the ways inventors experiment on the organization of their research efforts. Characterizing the changes between 1913 to 1958, Enos noted

> In petroleum cracking processes we observed two radical departures, that of moving from no research at all to research carried out by a few individuals, and that of shifting from a few individuals working independently and sporadically to large groups of individuals working in combination and in perpetuity (p. 233).

How did the changes come about? We assert that technological change involves inventors searching for ideas as well as inventive partners and research environments simultaneously. Over a period of time, there is strong tendency for inventors to gather with the successful inventors as the nuclei. With competition, the degree of successfulness will be positively related to the size of the nucleus. The approach here is thus quite different from the conventional emphasis on the relationship between firm size and inventive activities. Not only is firm size treated as endogeneous, we suggest the number of inventors (rather than asset values or market shares) as a more appropriate measure of firm size, because it reflects better the underlying incentive of forming research organizations. Naturally, if success and nucleus size are positively correlated, number of inventors and market share should be positively correlated also.

To study the emergence of research organization, the period of 1861-1938 in the petroleum industry seems to be most ideal. Enos marked 1938 as the beginning of the big four -- Research and Development Department of the Standard Oil Company (Indiana), Esso Research and Engineering Co., Universal Oil Products Co., and Houdry Process Corporation (p. 231-233). However, with the exception of Houdry, the other three were all winners emerging from a long experimentation process prior to 1938. Universal Oil Products, for example, was formed in 1914; and certainly, Standard Oil (Indiana) must have learned from the success and failure of the Burton process between 1913-1928. In this section we demonstrate how the emergence can be systematically analyzed by the career performance record of inventors.

We start our analysis by examining a patent catalogue compiled by David McKnight Jr. The catalogue has all patents relevant to the field of petroleum cracking between 1861 and 1938. McKnight examined a total of 2,886 patents covering the works of 1,003 inventors. For each patent, his catalogue gives the patent number, the name of the inventor, the application date, the date of issue, a general description of the patent, and the assignment records of the patents and the names (if any) of the assignees. The information allows a reconstruction of the career performance record of these 1,003 inventors. Table 1 is an example of such a record.

TABLE I

The Career Performance Record of C. J. Pratt

Year	Patent No.	Assignment Record
1929	1,741,535	Universal Oil Prod. Co.
1930	1,752,264	Unassigned
1931	1,810,574	Automotive Distillate Corp.
	1,827,107	Universal Oil Prod. Co.
	1,827,908	Universal Oil Prod. Co.
1932	-	-
1933	-	-
1934	1,946,947	Universal Oil Prod. Co.

Using the definitions on Table III, the following numerical values were assigned to describe C. J. Pratt: ALFE = 6, APA = 5, ASPC = .833, DISV = 0, IDISV = 0, JBS = 3, OLFE = 6, OPT = 4, ORG = 70, SPL = .833, TLFE = 6, TPA = 6, XALFE = .833, XOLFE = .667, XSPEC = .667, XTLFE = 1.0, YSPEC = 1.0.

What economic behavior, if any, can one infer about an inventor on the basis of these patent records? Consider the following behavioral postulate of an inventor: Suppose each inventor is endowed with a set of inventive potentials (to be defined in the next section) which can be improved via learning-by-doing, utilizing modern research facilities, and cooperation and communication with other inventors. However, he may not know the cost of extracting the inventive potentials even though he may have some strategies of ascertaining it. He also may not know the type of project and the research environment most suitable for his inventive potentials. Thus, he may experiment with different ideas under different research environments before the ideal combination can be identified. Furthermore, to be consistent with maximization, the search through experimenting must have the following properties: (i) An inventor will begin a project when its expected gain is greater than the expected cost, and he will quit when the expected gain is less than the revised expected cost. (ii) The more suitable is a research environment to an inventor's inert inventive potential, the longer time duration would an inventor remain with that research environment. Therefore, the ideal research environment of an inventor, to the extent that it exists, must be the one where he spent a majority of his time in, which often is also where a majority of his patents were invented.

Tracing the research environment via career patent record is not without problems: Firstly, some patents invented without employment contracts might be sold to a corporation before they are issued. Although Schmookler (1966, pp. 25-26) and others[7] do not think these instances are too frequent, we do not know how to measure the frequency of these cases. It would seem that the problem should not be particularly severe in situations where assignments to a particular firm occurred repeatedly over time (e.g., Universal Oil Product Co.

in Table I), because repeated sales are likely to be replaced by some long-term contractual relationship. In fact, the longer the assignment records, the more confidence one can have in using an assignment record to identify an employment contract.[8] (We note also that in McKnight's data set, 97.4% of inventors have two or less assignees in their career.)

Secondly, the relationship between patents and research effort is stochastic. Even though an inventor may be fully occupied with a certain project during a certain period of time, his patent record may show nothing. On the other hand, the lack of patent record may truly mean that the inventor has reallocated his efforts from research to other activities. In this paper, we shall assume that runs of long "droughts" (unproductive years) is still consistent with some (small) but continuous efforts, thus the possibility of inventors quitting inventive activities for a while and then later returning is ruled out. The assumption seems plausible in situations where the duration of droughts is short relative to the duration of successful patent records (e.g., C. J. Pratt appeared to be nonproductive in 1932, yet we will assume that he was working for Universal Oil Co. that year as well).

Research environments are quantified by the number of inventors assigning patents to the same organization. Table II gives the names of the organizations having more than five assignors and their corresponding number of assignors. The last column of the Table gives the name of the process (or the specialty) of the organization prior to 1938. The Table reveals that our method of quantifying research environments does coincides with the qualitative classifications given by the historians: the firms responsible for the prominent cracking petroleum techniques during the period were all included as relatively "large" research organizations in our sample.

Table II

Research Organizations with More Than Five Assignors

Names of Organizations and Addresses	Number of Assignors	Process
Alco Products, Inc. (Delaware Corp.), New York, NY	5	
Atlantic Refining Co., Philadelphia, PA	8	
Doherty Research Co. (Delaware Corp.), New York, NY	8	
E.I. DuPont de Nemours & Co., Wilmington, DL	5	
F.C. Fantz, Webster Groves, MO	5	
Gasoline Products Co., Newark, NJ	25	Cross
Gulf Refining Co. (Texas Corp.), Pittsburgh, PA	12	
Gyro Process Co., Detroit, MI	12	
Houdry Process Corp. (Delaware Corp.), Dover, DL	12	
I.G. Farbenindustria, Aktientgesellschaft, Germany	26	Catalytic Hydrogenation
Imperial Chemical Industries, Ltd., London, England	5	
Jenkins Petroleum Processing Co. (Wisconsin Corp.), Chicago, IL	5	
Petroleum Conversion Corp. (Delaware Corp.) New York, NY	7	
Phillips Petroleum Co. (Delaware Corp.), Bartlesville, OK	7	
Pure Oil Co. (Ohio Corp.), Chicago, IL	8	
Shell Development Co. (Delaware Corp.), San Francisco, CA	13	
Sinclair Refining Co. (Maine Corp.), New York, NY	26	
Standard Oil Co. of California, San Francisco, CA	10	
Standard I.G. Co.* (Delaware Corp.)	22	
Standard Oil Co., Whiting, IN	43	Burton

Table II (continued)

Names of Organizations and Addresses	Number of Assignors	Process
Standard Oil Development Co.** (Delaware Corp.)	31	Tube & Tank
The Texas Co. (Delaware Corp.), New York, NY	52	Holmes-Manley
Union Oil Co. of California, Los Angeles, CA	6	
Universal Oil Products Co. (Delaware Corp.), Chicago, IL	70	Dubb

*The Co. is owned jointly by the Standard Oil Co. of New Jersey and the I.G. Farbenindustrie A.G. of Germany and controls the hydrogenation patents of those companies.

**Subsidiary of Standard Oil Co. (New Jersey). In 1955, the company's name was changed to Esso Research and Engineering Co.

II. The earning profile of an inventor and its relationship with productivities have been modelled in a series of recent studies (Freeman 1977; Weiss and Lillard, 1978; Hansen, Weisbrod and Strauss, 1978; Weiss 1981). These studies emphasized various relationships between productivities, promotion posibilities, and earnings, but the interaction between productivity and research environments is seldom modelled. This section utilizes the assumption that patents come from a Poisson distribution to model the maximizing behavior of inventors.[9] We define the inventive potentials of inventor j as the set of Poisson distribution parameters $\lambda_{j1},\ldots,\lambda_{jn}$ in projects 1 to n. These inventive potentials may be exogeneously determined by talent, education and various socio-economic characteristics. They can also be endogeneously improved by the inventor's working effort, his learning experience, and his choice of research environment.

Patents in project i are heterogeneous, and its value, π^t_{ji}, comes from a distribution $f^t_{ji}(\pi_{ji})$ with mean $E^t_{ji}(\pi_{ji})$. If all inventors share public information in forecasting the parameters of this distribution, let's say via patent information in the past or via industry growth statistics, the index j can be suppressed, and inventor j's expected gain of project i at time t is $E^t_i(\pi_i) \cdot \lambda^t_{ji}$.

Inventor j has some initial estimate on the cost of extracting inventive potential i, C^0_{ji}. He will undertake project i if

$$E^0_i(\pi_i)\lambda^0_{ji} > C^0_{ji} \tag{1}$$

Inventor j also has alternative strategies of revising his initial estimate. The strategy assumed in this paper is that he will use the current actual cost of research as a prediction of expected future cost of research.[10] This implies the ex-ante cost of research would follow a random walk, i.e.

$$C_{ji}^{t} = C_{ji}^{t-1} + \varepsilon_{ji}^{t-1} \quad \text{where} \quad \varepsilon_{ji}^{t-1} \sim N^{t-1}(0,\sigma(\lambda_{ji}^{t-1})) \qquad (2)$$

To further simplify the problem, we assume inventors learning experience is on the cost of extraction only, and thus, inventive potential and the expected value of patent remain constant over time. The random component in (2) therefore comes from a stable normal distribution with mean zero and variance $\sigma(\lambda_{ji})$.[11] The reason for expressing σ as a function of λ_{ji} is that the Poisson distribution has the property that its variance also equals λ_{ji}. Thus, a high inventive potential inventor, by definition, also has a high variance in actual outcome. It is not unreasonable to assume that a larger variance in outcome also implies a larger variance in cost. I.e.,

$$\frac{d\sigma}{d\lambda_{ji}} > 0 \qquad (3)$$

Equation (2) can also be expressed as

$$C_{ji}^{t} = C_{ji}^{0} + \sum_{\tau}^{t-1} \varepsilon_{ji}^{\tau} \qquad (4)$$

with $C_{ji}^{t} \sim N(C_{ji}^{0}, t\sigma(\lambda_{ji}))$.

Inventor j will continue in research in project i so long as $E_i(\pi_i)\lambda_{ji} > C_{ji}^{t}$. He will quit when $E_i(\pi_i)\lambda_{ji} < C_{ji}^{t}$. This is a rational strategy because of our assumption that the best predictor of the next period's cost is the current period's cost. At any time in inventor j's career, the probability that he will continue with project i is

$$\begin{aligned} P_{ji}^{t} &= \Pr[C_{ji}^{t} < E_i(\pi_i)\lambda_{ji}] \\ &= \Phi\left(\frac{E_i(\pi_i)\lambda_{ji} - C_{ji}^{0}}{t\sigma(\lambda_{ji})}\right) \end{aligned} \qquad (5)$$

where Φ is the cumulative distribution function of the standard normal variable.

The probability that inventor j will quit at time t is the product of the probabilities of not quitting at periods $1,2,...,t-1$, and then stopping at t. I.e.,

$$\alpha_{ji}^{t} = (1-P_{ji}^{t}) \prod_{\tau=1}^{t-1} P_{ji}^{\tau} \tag{6}$$

The expected quitting time, or the career length of inventor j in project i is given by

$$T_{ji} = \sum_{t=1}^{\infty} t\alpha_{ji}^{t} \tag{7}$$

Since the probability function in (5) is solely a function of $(\frac{E_i(\pi_i)\lambda_{ji}-C_{ji}^0}{t\sigma(\lambda_{ji})})$, and since (6) and (7) are simply weighted sum of these probabilities, the expected quitting time T_{ji} is solely a function of the expected gain $E_i(\pi_i)$, the inventive potential λ_{ji}, and the initial cost endowment C_{ji}^0. I.e.,

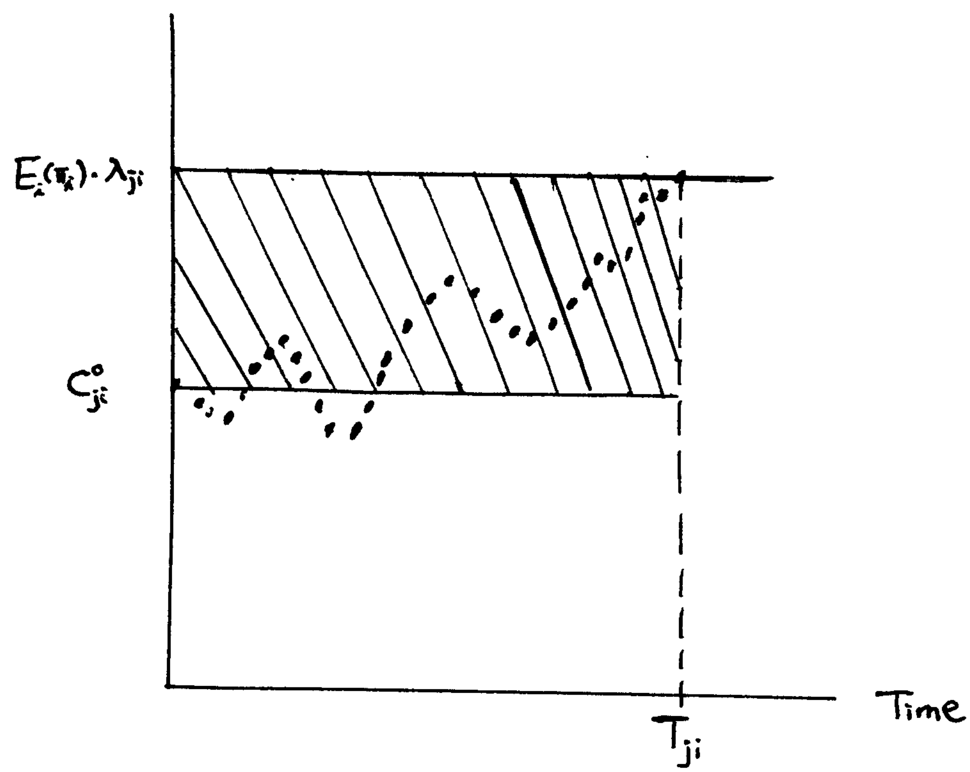
$$T_{ji} = G(E_i(\pi_i),\lambda_{ji},C_{ji}^0) \tag{8a}$$

and, assuming the inverse exists,

$$C_{ji}^0 = G^{-1}(E_i(\pi_i),\lambda_{ji},T_{ji}) \tag{8b}$$

Figure 1 illustrates the underlying stochastic process described above. The horizontal solid line represents the expected gain of project i. The actual patent record as well as the actual value of the patent varies around this mean. The dotted line represents the random walk of each period's cost of research. Inventor j will quit project i when the dotted line crosses the solid line for the first time. Several implications follow immediately from this formulation: (i) The higher is the expected gain of research, $E_i(\pi_i)$, ceteris paribus, the longer an inventor will continue in project i. (ii) The lower is the endowed cost of research, C_{ji}^0, ceteris paribus, the

FIGURE 1



longer an inventor is expected to remain working in project i. (iii) An increase in inventive potential, λ_{ji}, has ambiguous effects on quitting time: on one hand the expected gain of research is higher thus prolonging the research duration; on the other hand, the variance in gain as well as cost will also be higher, thus increasing the quitting probability.[12]

How should inventors' abilities be evaluated in this framework? A straightforward approach is to view an inventor simply as a capital asset capable of yielding a stream of net incomes. The value of this asset is approximately the quasi-rent as represented by the shaded area in Figure 1. More precisely, the expected net income initially anticipated from inventor j ought to be $E_i(\pi_i)\lambda_{ji} - C^0_{ji}$; and by the assumption of random walk, this net income is invariant over time ex-ante. Thus, the present value of inventor's ability in project i is

$$A_{ji} = \frac{1}{r}\,[E_i(\pi_i)\lambda_{ji} - C^0_{ji}][1 - (1+r)^{-T_{ji}}] \tag{9}$$

where r is the rate of discount and T_{ji} is the expected length of time inventor j will remain in project i.

Substituting (8b) into (9), we have

$$A_{ji} = \frac{1}{r}\,[E_i(\pi_i)\lambda_{ji} - G^{-1}(E_i(\pi_i),\lambda_{ji},T_{ji})][1 - (1+r)^{-T_{ji}}] \tag{10}$$

The significance of equation (10) is that for any given cohort of inventors, interpersonal differences in inventive ability in project i can be ranked solely in terms of λ_{ji} and T_{ji}. Interest rates may vary, expected gain in a project may be revised for a new cohort of inventors, but to the extent that inventors in the same cohort can share public information in making gain predictions, the ranking in the ability of inventors among the same cohort should not vary as long as the rankings of λ_{ji} and T_{ji} remain unchanged.

To what extent do inventors in the petroleum industry behave like a rational maximizing individual described here? To shed some light on this question, we first construct a list of variables characterizing the career performance record of an inventor in Table III. We believe these variables potentially provide much information for economic analysis along several directions:

(1) The Longevity of Inventive Career and the Duration of Contractual Relationship with Research Organization:

Intuitively, one would expect the maximization behavior and the productivity of an inventor to be reflected in terms of the length of time he remains as an inventor and the length of time he remains with various organizations (research environment). We measure the length of inventive career by the years between the first and last patent in an inventor's patent record, TLFE; we also measure the years between the first and last assignment patent, AFLE, and the years between the first and last patent belonging to the organization which owns most of the inventor's patents, OLFE. Expressing the latter two variables as proportions of the first variables, we have some indicators on the scope of research that were conducted within a "firm," and within the firm which owns most of an inventor's patents.

(2) The Intensity of Inventive Activity in General and in Various Research Environments:

Inventor's maximizing behavior and his productivity may also be evaluated in terms of total patents, or total patent per year — an intensity measure. We can count the total number of patents in an inventor's career, TPA; the number of patents he assigned to others, APA; and the number of patents he assigned to the organization that owns most of his patents, OPT. Then, by dividing each of these numbers by the time duration in (1) respectively, we obtain proxies for the intensity of inventive activity in general and under

TABLE III

List of Constructed Variables

For all variables below, an inventor's primary organization is defined as one owning the majority of the inventor's career patents.

AAPA	Adjusted assigned patents: APA - (JPT-XJPT)/2.
ALFE	Years between the dates of first assigned patent and last assigned patent. Enter as a missing variable if there are no assigned patents.
APA	The number of assigned patents. Enters as a missing variable if there are no assigned patents.
ATPA	Adjusted total patents: TPA - JPT/2.
ASPC	Percentage of assigned patents, APA/TPA. Equals zero if there are no assigned patents.
AXALFE	Adjusted assigned patents/assigned years.
AXOLFE	Adjusted organized patents/organized years.
AXTLFE	Adjusted patents/year.
DISV	Years between the dates of first patent in the inventor's career and the first patent assigned to his primary organization.
IDISV	Years between dates of first patent in the inventor's career and first assigned patent.
JBS	The number of different organizations the inventor assigned patents to. Unassigned patents are counted as one organization.
JPT	Total number of joint patents.
OLFE	Years between the dates of first and last patent assigned to the organization that owns a majority of the inventor's patent.
OJPT	Number of joint patents in the organization that owns the majority of an inventor's patents.
OPT	Number of patents belonging to the inventor's primary organization.

Table III (continued)

ORG	Number of inventors "employed" by the inventor's primary organization. If an inventor worked for more than one company, his primary organization was assigned on the basis of most patents to that company. In the case of a tie, the inventor's latest job was chosen. Independent inventors have ORG equals zero.
PJPT	Percentage of joint patents, JPT/TPA.
SPL	For independents, SPL equals the number of unassigned patents divided by years between the first and last unassigned patents, for assigned inventors, SPL equals XALFE.
TLFE	Years between the first and last patent in an inventor's career life.
TPA	Total number of patents in career life.
XALFE	Number of assigned patents divided by years between the first and last assigned patents, APA/ALFE. Enters as a missing variable if there are no assigned patents.
XJPT	Number of joint unassigned patents.
XOLFE	Number of patents belonging to inventor's primary organization divided by years associated with that organization, OPT/OLFE.
XSPEC	Number of patents belonging to inventor's primary organization divided by the total number of the inventor's patents, OPT/TPA.
XTLFE	Number of total patents in the inventor's career divided by length of his career, TPA/TLFE.
YSPEC	Number of years associated with the inventor's primary organization divided by the length of his career, OLFE/TLFE.

different research environments. We labelled these variables so constructed as XTLFE, XALFE, and XOLFE.

(3) The Diversity of Inventive Ability and the Degree of Specialization:

We measure the diversity of inventive ability by the number of assignees in an inventor's career, JBS. The implicit assumption here is that two different assignees do not engage in the same line of research. There are two reasons for this to be so: first, inventors' employment contracts in the real world uniformly require the inventors to assign all relevant patents during employment to the research organization.[13] If this is enforced perfectly, an inventor can assign patents to different assignees only because he engages in different projects. Second, there is much resource duplications if two firms engage simultaneously in the same line of research. If such social waste can be eliminated via private contracting, one could very well argue that the two firms would have merged and thus, separate assignees interested in the same line of research would not have been observed in the first place.[14]

The diversity measure so constructed is to be distinguished from the extent of specialization, which can be measured by the proportion of patents assigned to the organization that owns most of the inventor's patents, XSPEC. The two measures are not contradictory. An inventor might have ten assignees in his career, thus demonstrating great diversity; yet he might assign 99% of his patents to only one of the assignees, thus, he is also highly specialized.

(4) The Extent of Cooperative Inventive Works:

We measure the degree of cooperative work by counting the number of joint patents in an inventor's career, JPT. We also make a distinction between the number of joint unassigned patents, UJPT, and the number of joint patents assigned to the organization that owns most of the inventor's patents, OJPT. Besides providing information on the extent of joint works, these measures allow adjustment in the intensity measure of productivity in (2), since one might speculate that the contribution by an inventor in a joint patent should be reduced according to the number of co-patentees.

(5) The Information Cost of Revealing Comparative Advantage:

It takes time for both the inventor and his employers to discover his comparative advantage. The information gathering mechanism may also differ between large and small research organizations. The magnitude of these search costs can be reflected in terms of the years between the first patent in an inventor's career and the first patent assigned to the entity which owns most of his patents, DISV, and the years between the first patent in an inventor's career and his first assigned patent, IDISV.

The summary statistics constructed from (1) to (5) should reflect the maximizing behavior of inventors, which in turn affect as well as being affected by various research environments. In Table IV, we sort inventors into two categories based on their ideal research environments (c.f. p. 6, point (ii)). The first has most of their patents unassigned which means that most of the research were conducted without employment contracts — a category casually known as "independent." The second has most of their patents assigned on or before the patents were issued, which means that most research was conducted with an employment contract — a category we can loosely label as "employed" inventors. Column One lists the set of variables we are comparing. Column Two gives the means, the standard deviation, and the number of observations on those variables for the "independent" inventors. Columns Three, Four, and Five give the same for the "employed" inventors. Columns Six and Seven report the t-statistics on the differences of the means by assuming equal and unequal variances.

TABLE IV

Summary Statistics of Independent and Employed Inventors

(All Observations Included)

Variable	Independent			Employed				
	μ	σ	n	μ	σ	n	t_{eg}	t_{uneq}
(1) Total Patents (TPA)	1.954	1.961	281	3.978	9.468	722	-3.55	-5.45
(2) Career Life (TLFE)	3.067	4.675	281	3.398	4.26	722	-1.07	-1.03
(3) Patents/Year (XTLFE)	.999	.455	281	1.144	.812	722	-2.83	-3.57
(4) Assigned Patents (APA)	1.667	1.451	33	3.807	9.343	722	-1.31	-4.98
(5) Assigned Career Life (ALFE)	3.152	5.44	33	2.954	3.55	722	.303	.206
(6) Assigned Patents/year (XALFE)	.906	.328	33	1.177	.855	722	-1.81	-4.13
(7) Patents in "Ideal" Research Environment (OPT)	1.754	1.512	281	3.61	9.12	722	-3.38	-5.27
(8) Years in "Ideal" Research Environment (OLFE)	2.484	3.572	281	2.616	3.045	722	-.588	-.540
(9) Patents/Year in "Ideal" Research Environment (XOLFE)	1.0218	.428	281	1.221	1.218	722	-2.69	-3.89
(10) Alternative Measure of Research Intensity (SPL)	1.022	.428	281	1.177	.855	722	-2.900	-3.798
(11) Diversity (JBS)	1.142	.448	281	1.230	.544	722	-2.397	-2.61
(12) Specialization in "Ideal" Research Environment (XSPEC)	.955	.1311	281	.933	.157	722	+2.25	+2.08
(13) Specialization in Assigned Patents (ASPC)	.044	.131	281	.965	.113	722	-110.68	-103.86
(14) Joint Patents (JPT)	.456	.836	281	1.37	4.304	722	-3.53	-5.45
(15) Probability of Joint Work (PJPI)	.292	.446	281	.407	.450	722	-3.63	-3.65
(16) Joint Patnets in "Ideal" Research Environment (OJPT)	.431	.790	281	1.27	4.14	722	-3.37	-5.20
(17) Discovery Time of First Employment Contract (DISV)	.409	2.399	281	.584	2.273	722	-1.08	-1.05
(18) Discovery Time of "Ideal" Research Environment (IDISV)	3.212	5.195	33	.4017	1.970	722	7.16	3.098

On measures of longevity (Rows 2, 5 and 8), there appears no noticeable difference between the two groups. On measures of intensity, however, assigned inventors' summary statistics seem significantly higher. Both total patents and patents per year of the assigned inventors are higher than that of the independent inventors (Rows 1 and 3). The discrepancies persist for assigned patents and assigned patents per year (Rows 4 and 6). They also persist when both the independent and the employed inventors have found their respective specialties (i.e. comparing an employed inventor's assigned patent in his "ideal" research environment to an independent inventor's unassigned patent, Row 7, and comparing the patents per year when an employed inventor is with his "ideal" research environment to the patents per year when an independent inventor is by himself, Row 9). Similarly, the assigned patents per year of the employed inventors are higher than the unassigned patents per year of the independent inventors (Row 10).

Comparisons of other descriptive statistics yield the following picture. The diversity of employed inventor as measured by the number of assignees is greater than that of independent inventors (Row 11), but the extent of specialization is greater among the independent group than the employed inventor group (Row 12). The frequency of joint work is higher among employed than independent inventors (Row 14, 15 and 16). We also detect no significant difference in the time it takes an employed/independent inventor to discover his comparative advantage (Row 17). However, independent inventors were employed much later in their career lives than the assigned inventors (Row 18). In other words, independent inventors, if ever employed, are independent first and then employed rather than the other way around. This evidence is partially inconsistent with the common notion that inventors' employment contracts are used to diversify risk. The uncertainties concerning the productivity of the inventor ought to be less when he ages; and thus, the incentive to diversify risk should be lower at the latter part of his career. Also, some argue that a superior inventor would like to charge monopoly price on his service when his ability is better known. If so, this should occur at the latter part of his career. The evidence in Row 18 seems inconsistent with both of these notions.

III. Simple patent counts undoubtedly ignore the economic value of patents. The model in Section II, however, suggests a meaning in which such heterogeneity problems can be set aside. If the value of patents come from a distribution and if inventors share public information on the distribution, differences in inventors' abilities will be reflected totally in terms of difference in λ_{ji} and T_{ji}, (see equation (10) in the last section). The two variables in essence form a dual proxy for inventor's ability. In this section, we examine how inventors with various characteristics would sort themselves into different research environments. The particular dimension of research environment we are interested in is the size of the organization. Are higher ability inventors (by λ and T standard) more likely to be in larger organizations? What are other characteristics typical among inventors of large corporations?

We answer the above questions by first assuming that λ is truly exogeneous; and second, by assuming that λ is partially endogeneous. The second procedure is motivated by the speculation that the higher patent performance record of inventors in large corporations may have resulted because large corporations, often assisted by able and experienced patent attorneys, are likely to make excessive patent claims. On both theoretical and empirical grounds, however, the speculation should not be taken for granted. On theoretical grounds, it is not clear that the best patent attorney necessarily earns more by working for a firm; it is also not clear that the best attorney always wants to maximize the number of patents per idea. Such issues depend largely on the prevalent forms of contracts between patent attorneys and their clients, which have not been investigated thoroughly in the literature yet. From the inventor's point of view, it also does not necessarily follow that employed inventors would have a higher propensity to patent than an independent inventor. In fact, one could argue that independents should have a greater incentive to patent their innovations than employed inventors because the evaluation and the diffusion of ideas in the former case have to rely totally on market mechanism, whereas such activities in the latter case can occur without explicit market transactions. It goes without saying that market transactions require stronger property right protection than non-market transactions. In addition, there exist some empirical studies suggesting that the largest firms in the U.S. usually barely held their own in the receipt of invention patents despite their disproportionate share of both government and private R&D spending.[15]

A. Exogeneous λ

We ran a linear regression of the size of research organization (ORG) on the ability index (λ and T) together with a vector of inventor's charactersitics, i.e.

$$ORG = f(A(\lambda_{ji}, T_{ji}), x) \qquad (11)$$

We utilize patents per year and total career life of an inventor as proxies for composites of λ_{ji} and T_{ji} respectively. x includes (i) the probability of doing cooperative work — a potential reason for inventors to join large organizations, ala Coase, 1937, and Alchian and Demsetz, 1972.

(ii) the diversity and specialization measure, and (iii) a time proxy to account for the different entry dates of inventors.

We report the findings of (11) in Table V (a) and (b). Table V (b) adjusts the measure of patents per year by counting a joint patent as only half a patent. In the regressions on both Tables, the coefficients on inventive potential, λ, and career length, T, are significantly positive, suggesting that more able inventors do have a tendency to be associated with large research organizations. The coefficient on the entry date suggests that new entering inventors have a tendency to join the large research organizations. However, with the adjusted inventive potential measure in the next model, the significance disappear (c.f., p. 28). The coefficient on joint work is not significant, suggesting that inventors in large research organization are not characterized by a high frequency of joint works. The negative coefficients on diversity may suggest that large firms have a tendency to select a more "narrow minded" inventor; however, the coefficients are certainly also consistent with the relative efficiency of large firms in enforcing employment contracts. Finally, there are no signficiant correlations observed between size of research firms and the degree of specialization in that firm (regression results omitted).

B. Endogeneous λ

We ran a simultaneous equations model by adding a function determining λ_j together with (11):

$$\lambda_j = \lambda_j^0 e^{Y\beta} \tag{12a}$$

or

$$\ln \lambda_j = \ln \lambda_j^0 + Y\beta \tag{12b}$$

TABLE V(a)

Equation 11: Characteristics of Inventors in Large and Small Firms

Dependent Variable is Size of Research Firm, ORG

(Numbers in parentheses are t-values)

	Inventive Potential (LXTLFE)	Career Life (LTLFE)	Entry Date (BYPT)	Diversity (JBS)	Joint Work (PJPT)	R^2
(1)	10.946	5.704				0.0829
	(8.25)	(7.57)				
(2)	9.560	6.691	0.602			0.1548
	(7.45)	(9.15)	(9.22)			
(3)	9.628	8.863	0.598	-6.677		0.1723
	(7.58)	(10.25)	(9.24)	(-4.59)		
(4)	10.926	5.805			2.003	0.0847
	(8.24)	(7.67)			(1.39)	
(5)	9.561	6.697	0.601		0.156	0.1548
	(7.45)	(9.13)	(9.09)		(0.112)	
(6)	9.627	8.861	0.598	-6.679	-0.076	0.1723
	(7.57)	(10.23)	(9.15)	(-4.59)	(-0.05)	

LXTLFE is the log of XTLFE which is a proxy for average λ_{ji} across different projects i undertaken by inventor j.

LTLFE is the log of TLFE which is a proxy for career life.

BYPT measures entry date of inventors, JBS measures the number of assignees and PJPT measures the percentage of joint patents in one's career.

TABLE V(b)

Equation 11: Characteristics of Inventors

Dependent Variable is Size of Research Firm, ORG

(Numbers in parentheses are t-values)

	Adjusted Inventive Potential (LAXTLFG)	Career Life (LTLFF)	Entry Date (BYPT)	Diversity (JBS)	R^2
(1)	7.021 (6.18)	4.524 (6.18)			0.0566
(2)	6.763 (6.24)	5.873 (8.26)	0.650 (9.93)		0.1413
(3)	6.899 (6.42)	8.097 (9.51)	0.645 (9.96)	-6.806 (-4.65)	0.1595

LAXTLFG is the log of AXTLFE which is the adjusted patents/year with joint patents counting only as half a patent. All other variables are explained in Table V(a).

The preceding discussion on p. 22-23 suggests that a key determinate of λ may be the patent facilities in large corporation (proxied by firm size, ORG). In addition we also expect inventive potentials will be affected by changes in the state of the art (proxied by the entry date), the differential cost of obtaining patents (proxied by assigned patents), and cooperation and communication with other inventors (proxied by probability of joint works).

We use 2SLS to estimate the simultaneous equations of (11) and (12b), and the estimates of the coefficients in the structural equations are reported in Table VI. Superior inventors with high λ and T continue to be located in large firms, coefficients of these two variables in the first structural equations are highly significant. Several additional information are revealed also: First, contrary to intuitive belief, large organizations do not generate a higher propensity to patent; in fact, the coefficients on ORG in the structural equation of (12b) demonstrates a negative effect on the propensity to patent -- a result that is consistent with previous patent-R&D statistical studies (cf., fn. 4). The significant positive coefficients of ASPC in the structural equations (11), however, suggest that assigned patents may be intrinsically different from unassigned patents; it is also consistent with the speculation that assigned patents may be easier to be patented. The coefficients of entry dates in both structural equations also have interesting interpretations: the trend of new entrants working in larger firms observed earlier in Table V apparently arises because new entrants are more prolific and thus more highly valued by large firms. Entry date in (12) is used as a proxy for past accumulated knowledge, and its positive significance implies that the information had enhanced rather than diminished the inventive potential of the new entering cohorts. On the other hand, entry date in (11) is used as a proxy for the preferences of organization and new inventors

TABLE VI

Simultaneous Equation -- Equation (11) and (12)

	Structural Equation (11) Dependent Variable is firm size						Structural Equation (12b) Dependent Variable is LXTLFE				
	LXTLFE	LTLFE	BYPT	JBS	PJPT	R^2	ORG	ASPC	PJPT	BYPT	R^2
(1)	123.027 (5.34)	30.486 (5.58)				0.0303	−0.062 (−4.62)	1.327 (4.56)	−0.107 (−1.08)	0.026 (4.34)	0.0266
(2)	135.913 (3.76)	33.011 (4.20)	−0.151 (−0.50)			0.0254	−0.062 (−4.63)	1.327 (4.56)	−0.107 (−1.08)	0.026 (4.34)	0.0266
(3)	136.943 (3.75)	35.927 (4.37)	−0.162 (−0.53)	−8.355 (−1.72)		0.0270	−0.035 (−5.29)	0.774 (5.17)	−0.050 (−0.781)	0.018 (5.13)	0.0400
(4)	122.778 (5.33)	30.466 (5.58)			0.661 (0.16)	0.0305	−0.0619 (−4.63)	1.327 (4.55)	−0.107 (−1.08)	0.026 (4.34)	0.0266
(5)	136.325 (3.75)	33.135 (4.19)	−0.160 (−0.52)		0.996 (0.22)	0.0253	−0.0619 (−4.63)	1.327 (4.56)	−0.107 (−1.08)	0.026 (4.34)	0.0266
(6)	137.217 (3.75)	36.003 (4.36)	−0.169 (−0.55)	−8.331 (−1.71)	0.711 (0.15)	0.0269	−0.035 (−5.29)	0.774 (5.17)	−0.050 (−0.78)	0.018 (5.13)	0.0400

LXTLFE represents λ, LTLFE represents T, BYPT represents entry dates, JBS represents number of assignees, PJPT represents percentage of joint patents, ORG represents firm size, ASPC represents percentage of assigned patents.

beyond the ability measures, its insignificance suggests indifference. Finally, the coefficients of JBS, the diversity index, are still negative in the structural equations of (11).

Perhaps the most surprising result in Table VI is the coefficients on joint works. One would think that a cooperative inventor (as measured by the probability of joint work) not only would be welcome in large research organ izations (equation (11)), but he himself should benefit from the interaction as well (equation (12)). However, the coefficients in neither structural equations demonstrate any significance.

Conclusions and Remarks

Superior inventors have a tendency to sort themselves into large research organizations, or so it seems in the petroleum refining industry. This result has two important implications: first, in a stochastic sense, one should expect more useful innovation to emerge on the average from large firms. This apparently conflicts with the prevalent view that technical advances arose mostly from small and independent concerns. The latter view can be misleading: it suggests that large firm environments are counter-productive to new ideas and small independent concerns are more efficient alternatives to channel new ideas; it also implies that the probability of technical advances would increase if small independent concerns are subsidized. If in actuality, superior inventors are more likely to be in large organizations, the factors alleged as counter-productive in large firms perhaps should be interpreted as the results of success rather than hindrance to success. The inertia and the communication problems in an existing research organization may indeed lead to the separation of some ex-post superior inventors from its parent companies; but with free entry in setting up research organizations, these costs of bigness would not be heavily taxing technological progress. In fact, if the departing inventors are ex-post successful, the size of his research organization would grow, and eventually, inertia in a different direction (perhaps a larger magnitude than the previous one) would simply replace the old. The evidence presented in this paper is at least consistent with this line of thinking.

A related but different line of inquiry on our study can be made regarding the underlying motivation behind the forming of research organizations. The predominance of superior inventors among large firms is consistent with the explanation that a research organization is formed to capture the return to nonpatentable research.[16] Team production, on the other hand, appears to be insignificant in inventive activity. If the production of ideas involves only team efforts of a small scale, the existence of large research organizations is indeed puzzling. Admittedly, our measure of teamwork proxy may be imperfect, and additional information is needed for more conclusive statements. However, the approach and the evidence in this study may provide a starting point for formulating hypotheses in this relatively unexplored area of research.

Footnotes

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[1]A complete list of references can be found in Scherer's Industrial Market Structure and Economic Performance, 2nd Ed., pp. 413-423.

[2]For example, see E. Mansfield, The Economics of Technological Change, p. 216; R. L. Nelson, M. J. Peck, and E. D. Kalachek, Technology Economic Growth and Public Policy, p. 58.

[3]With zero transaction cost, it does not matter whether the problem is analyzed in terms of the owner of research facilities hiring inventors, or vice versa. Resource allocation will be identical for both types of arrangements. See Alchian & Allen, Ch. 8, p. 166-168; Cheung (1969).

[4]See Scherer, p. 418; Schmookler, "Inventors Past and Present," Review of Economics and Statistics, Vol. 39 (August 1957). Another interpretation of this result is that unobservable characteristics associated with organizational size may have negative effects on productivity, but balancing this cost with the gain of forming large research organizations, it still pays the superior inventors to be associated with large research organizations. I thank an anonymous referee for the suggestion.

[5]For example, see Williamson, Daum et al (1959) and John L. Enos (1962).

[6]See John S. McGee (1966) and Ward S. Bowman Jr., (1973).

[7]See U.S. Patent and Trademark Office, Technology Assessment & Forecast, Ninth Report, March 1979, p. 44-49.

[8]In situations where only a single assignment record is found (e.g., Automotive Distillate Corp.) we are less certain about the severity of the problem. It seems plausible that inventors can "accidentally" come across an idea not covered under an existing employment contract, but choose to sell out to another research organization, nevertheless. The case is analogous to an amateur selling the fish he caught in the harbor to a local fish store. On the other hand, there is always the possibility that the inventor is a part-time employee in another organization. In any case, the productivity measure of an inventor should certainly include these patents because part of the ability of an inventor is indeed his ability to come up with "accidents."

[9]Although the use of Poisson distribution to describe patenting activities is not entirely appropriate, see Hausman, Hall and Griliches, "Econometric Models for Count Data with an Application to the Patents — R & D Relationship" (Harvard University, Discussion Paper No. 845, 1981), we adopt the formulation for simplicity purposes.

[10]The alternative is to adopt some forms of Bayesian revisions. However, we do not have enough socio-economic information on inventors to differentiate their learning behavior.

[11]The units of C is chosen in such a way that the probability of having a negative cost is negligible.

[12]The possibility is consistent with the observed -0.07 simple correlation between estimates of λ and T in our data set.

[13]Fredrik Neumeyer, with legal analysis by John C. Stedman, The Employed Inventor in the United States: R & D Policies, Law and Practice, Ch. 2 (1971).

[14]See Ben T. Yu, "A Contractual Remedy to Premature Innovation: The Vertical Interpretation of Brand-Name Specific Research," forthcoming, Economic Inquiry.

[15]See footnote 4.

[16]See Yu (1981), "Organized Research, Basic Information, and the Productivities of Inventors," UCLA, mimeo.

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