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# Highly innovative small firms in the markets for technology

**Diana Hicks and Deepak Hegde**

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School of Public Policy
**Georgia Institute of Technology**
**D. M. Smith Building**
**Room 107**
**685 Cherry Street**
**Atlanta, GA 30332 - 0345**

# Highly innovative small firms in the markets for technology[1]

**Diana Hicks & Deepak Hegde**[a]

***Abstract***

Long-lived small firms with a substantial, public record of innovative success are the focus of this paper. We label such firms "serial innovators" and argue that they are often specialist suppliers in markets for technology. To survive as specialist suppliers, firms must produce technology that is broadly tradable. Using Arora, Fosfuri and Gambardella's markets-for-technology framework, we hypothesize that such technology has certain characteristics. It is: high quality, general purpose, broadly based, quite basic, and concentrated in newer generations of technology. We find that serial innovators, survivors among the specialist technology suppliers, have mastered innovating in technology with these characteristics. This helps explain why these firms have become serious players in these markets – at least for a few years until a new generation of technology emerges.

***Keywords:*** small-firms, innovation, patents

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[a] School of Public Policy, Georgia Institute of Technology, 685 Cherry Street, Atlanta GA, 30332. Tel: +1 404 385 6015; Fax: +1 404 385-0504; email: diana.hicks@pubpolicy.gatech.edu, deepak.hegde@pubpolicy.gatech.edu

## *Introduction*

Small firms have long engaged the interest of students of innovation. The innovative efforts of small firms embody a tension between serious barriers and distinct advantages relative to large firms.[a] Establishing empirically the balance between these forces involved investigating whether small firms innovated more or less efficiently than large firms.[b] From the policy viewpoint, new technology-based firms have been studied for their promise of growth and new jobs. Such studies have assumed that small firms were mini-large firms: Were mini-large firms more or less efficient innovators than large firms? Which mini-large firms would grow large?

Large size has been seen as the natural outcome of small firm survival and success. In this paper we establish the empirical reality of long-lived, highly innovative small firms. We find innovative firms that have survived beyond the entrepreneurial moment yet remain small. Such firms are so unlike the giant multi-national that their relative innovative efficiency seems irrelevant. We argue that these firms, which we name "serial innovators", are often successful specialized suppliers of technology.

Serial innovators are part of an innovative division of labor. Several scholars, most prominently Stigler (1951), and more recently Von Hippel (1994, 1998) and Helpman (1998), have argued that the increasing division of labor in innovation must be understood in order to understand the sources of organizational change and economic growth in the twenty-first century. Today we see markets for technology developing, encouraging the innovative division of labor, and the existence of small high-

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[a] See for example, Cohen & Klepper (1991), Feldman (19970, Freeman & Soete (1997), Koen, (1992), Obermeyer, (1981), Romeo (1984), Rothwell & Zegveld (1982), Rubenstein & Ettlie (1984).

[b] See: Edwards and Gordon (1984), Gellman Research Associates (1982), Pavitt et al. (1987), Acs and Audretsch (1987), Cohen and Klepper (1996). Kamien and Schwartz (1975) provides an excellent (if dated) review of key studies concerning innovation and firm size.

technology firms. Arora, Fosfuri and Gambardella analyze in detail markets for intermediate technological inputs, that is markets in which transactions create new technology. They include within their remit contract research, technology licensing, R&D joint ventures of various kinds, sale or licensing of research tools and other types of technical services (Arora, Fosfuri and Gambardella, 2001, p 6). When such markets reflect a division of innovative labor involving specialist suppliers of technology, we are likely to find small firms.

Success in technology markets does not come easily; relatively few small firms survive. We examine here the survivors, and take advantage of that fact to explore the characteristics of technology likely to be more tradable by comparing serial innovator technology with that of large firms innovating largely for in-house use. We hypothesize that compared to in-house technology, tradable technology will be: higher quality, more general purpose, more broadly based, more basic, and more concentrated in newer generations of technology. Our results have implications not only for the technology strategy of small firms, but also for others entering technology markets, such as universities or public sector research laboratories.

### *What is a serial innovator?*

We label as “serial innovators” small firms with a sustained, public record of successful technical advance. Using a standard definition, “small” firms are those with 500 or fewer employees. We use patent information as a public record of sustained technical advance. We examine here the set of U.S. firms with 15 or more USPTO patents issued between 1996 and 2000. To be included an organization had to be independent, for-profit, not bankrupt, not a joint venture and not foreign owned during the first half of 2002 when the data were collected. All establishments and subsidiaries were unified to the ultimate parent company; their patents counted towards the parent firm patent count. The population of US firms with more than 15 patents issued over the period 1996-2000 encompasses 1,071 firms. One-third of these or 356 are small firms and 27 are of unknown size.[c] The firms own 193,976 patents (here as in what follows "patents" refers to type 1, utility patents that list a U.S. inventor address and were issued by the USPTO between 1996 and 2000) and small firms account for 6% of these patents.[d] Hence, of the firms with 15 or more patents, 33% are small firms, which own 6% of the patents.

For a small firm, owning 15 patents is quite an achievement. Therefore, we are not looking at start-up firms, the promising beginnings that grab most media attention. Our small firms are survivors and have attained a track record of credible technical achievement over at least five years. A good description of such firms was devised by Leigh Buchanan, a journalist with Inc. magazine, who labeled them "serial innovators".[e] She contrasts serial innovators with serial entrepreneurs. Small firms normally start with a great idea. The firm is founded to exploit the idea, to get it out into the marketplace. If it fails the firm disappears; if it works the entrepreneur may sell out. Even if the idea works and the firm is not sold, the next idea, or a process to generate more ideas becomes a problem, and often the small firm disappears after the first idea is worked through. Whatever the outcome, in the U.S. the entrepreneur is likely to go on to start another firm, and there are many "serial entrepreneurs." Serial innovators are firms distinguished by their success in sustaining innovation around the first idea or by having moved beyond the first idea while maintaining their innovative edge.

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[c] The patenting characteristics of the firms of unknown size suggest they are small, and we include them amongst the small firms.

[d] Small firms account for a large share of patents produced by organizations with less than 15 patents 1996-2000. We estimate that overall small firms account for about 43% of U.S. company-owned patents. This is quite close to their share of employment. See Hicks (2002).

[e] The August 2002 issue of Inc. magazine contains profiles of some of these firms.

Although these firms are not mini-large firms, there are ways in which the serial innovators are more similar to large patenting firms than to the general population of small firms. For example, serial innovators concentrate in industries where technical innovation and patent protection are important. The large firms among the largest 1,000 patentees differ from other large firms in precisely the same way. The firms are largely manufacturing companies with almost one-quarter found in semiconductors, pharmaceuticals, biotechnology and medical devices/equipment – industries that account for about 2% of US manufacturing firms.

Beyond industry differences, serial innovators differ from other small firms because they have invested substantial time and money in innovation. Their innovative efforts can look like best practice in large firms. Unusually for small firms, the firms are also very likely to have an R&D group and to have given some thought to how it was set up and managed. There tends to be formal structures, committees etc., for approving funds for potentially patentable ideas and then moving those projects toward the patent stage. Compensation is often tied to patents in the form of bonuses. Buchanan found that the firms tend to set a goal that a certain percentage of their earnings should come from new products. 3M is famous for doing this, but many of these small firms do the same.

### *Serial innovators and the markets for technology*

Despite the similarities between the R&D efforts of innovative small and large firms – we maintain that the small firms and their technology are different. This is because serial innovators are often specialist suppliers of technology. Buchanan's interviews highlighted the specialist technology supplier character of the firms. She found that a subset of these firms, especially in the pharmaceutical and biotechnology areas, maintain their R&D with support from large firms and are essentially outsourced R&D operations for large firms. She also concluded that unlike most small firms, these firms tended to have a core technology rather than a core product. They seemed to be interested in not just a new thing, but also a new and different way of doing something, a new process. In other words at their heart the firms were technology suppliers rather than product manufacturers.

That the small firms tend to be specialist suppliers of technology is also suggested by their concentration in technologies where markets are well developed. Arora, Fosfuri and Gambardella describe the substantial evidence for technology markets in chemical plant design, software, biotechnology, drug discovery and semiconductors. We find that the serial innovators are over represented among firms patenting in those technologies.

Overall, small firms have a 6% share of patenting and one-third of the firms are small. In biotechnology however, small firms produce one-quarter of the patents in this study and account for 71% of the patenting firms.[f] In pharmaceuticals, chemicals and agriculture the small firm share of patenting ranges from 8% to 19%, though only in pharmaceuticals does the share of firms that are small exceed the average. These areas are closely related to biotechnology; some genetic engineering falls under agriculture, and small firms with a high proportion of chemistry patents tend to be engaged in drug delivery, DNA chips, combinatorial chemistry and the like. In semiconductors 44% of the patenting firms are small, though their share of patenting is not high at 5%. This suggests that although small firms are relatively active, large firms have a higher propensity to patent than in other areas and so overshadow small firm patent counts.[g] The concentration of small firm patenting in these areas supports the notion that the serial innovators tend to be suppliers of technology because these are areas in which markets for

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[f] Using a classification of patents into 30 broad technology areas. This classification is based on the first listed IPC or international patent classification code on each patent. The classification was designed to roughly align with the SIC or NAICS classifications.

[g] That large IT firms have recently dramatically increased their propensity to patent is reported in Hicks et al., 2001. In our data, while small firms comprised 30% of all firms patenting in the “computers and peripherals” area which includes software, they owned only 3% of the patents assigned to these technologies.

technology are well developed.  In the case of software, however, small firm patenting is weak.  It may be that the computers category which contains software is too broad or it may be that patents are irrelevant for fast moving small firms and are used by large firms simply because their routines for protecting technology traditionally include patenting.

Among the strongest areas of small firm patenting are medical electronics and medical equipment, an area not addressed by Arora, Fosfuri and Gambardella.  Venture capital interest in this area is strong as reported by Red Herring, and there is a market for firm acquisition with Johnson & Johnson, Boston Scientific and Medtronic buying firms to acquire their technology.  In medical electronics and medical equipment development costs are considerably lower than for pharmaceuticals and FDA approval is easier making the market quite attractive (Stein, 2003).  The same factors no doubt enable small firms to become manufacturers, and the technology has similarities to instrumentation which has been a long-standing strength of small firm innovation (Rapoport, 1990; Shimshoni, 1970).  Further investigation is needed to ascertain whether a market for medical device technology is developing, and to identify the factors driving developments.

“Unclassified” technologies also represent a small firm strength.  Here the story is different. Unclassified patents encompass, amongst other things, patents on fun things – golf, snowboarding, toys, casino gaming etc.  Thirteen firms have more than half of their patents in the unclassified category, and eleven of these are gaming or leisure firms, including Mattel, Hasbro, Huffy (bicycles) and Callaway Golf.  21% of the patents with the words: toy, game, gaming, snowboard or golf in their titles belongs to small firms.  This is not a traded technology, but it may be one with outstanding attractions for serial innovators.  First, like medical devices and instrumentation, the complementary assets needed to realize the value of an innovation may be affordable for small firms who can thus succeed in manufacturing and marketing.  Second, small firm establishment often is driven by an individual’s passion.  If a technologist’s passion is golf, or snowboarding or toys, establishing an innovative equipment firm is a natural expression of that. In sports, there would be substantial rewards to the entrepreneur, who would enjoy a lifestyle in close contact with users of their equipment – i.e. others like themselves passionate about the game or sport - from whom they can glean ideas for innovations. Perhaps they attain a central position in the sporting community through their supply of high-end equipment to the elite. Perhaps therefore, the lifestyle benefits of running such a business exceed the gains possible by selling out. This is probably also true because in the absence of opportunities for technology trading, big investor money does not swirl around snowboarding and golf in quite the same fashion as it does around semiconductors and biopharmaceuticals. Therefore in this area small firms may be more likely to become serial innovators.

Firms that patent heavily are largely manufacturing firms. Therefore, one marker of a specialist technology supplier among firms that patent heavily may be the absence of manufacturing. We examined company descriptions for a sample of 140 firms with less than 45 patents 1996-2000, 53 large firms and 85 small firms.[h] 91% of the large firms were manufacturers, that is produced a product, while 66% (56) of the small firms were manufacturers. Although the presence of manufacturing may indicate that a firm's primary business in not trade in technology, at least three of the small manufacturers (and one large) also consult or provide technology services. The remainder of the firms did not seem to produce material goods at all. 21% of the small firms (or 18 firms) were research and/or development firms. Six firms, 3 large and 3 small, sold services – beyond development or research services. Eight firms, 2 large and 6 small were software firms. One small firm was a "fabless" semiconductor manufacturer and another called itself a technology supplier. This supports the idea that the small firms tend to be specialist suppliers of technology. Large patenting firms are likely to be manufacturers, while small patenting firms

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[h] The sample comprised firms whose names began with A-Biop and M-Prog. Firms for which we could not obtain a description were excluded.

much less so. For a substantial fraction of the small firms, their only business is technology trade through R&D, technology services or semiconductor chip design.

Data on co-assigned patents also support our argument that small firms are more involved in technology trade. Co-assigned patents are those jointly owned by two or more organizations. 3.2% of small firm patents are co-assigned, compared to 1.7% of large firm patents. That is, small firm patents are co-assigned 1.8 times as much as large firm patents. Co-assigned patents are relatively rare, because organizations do not like to share ownership of their technology. 1.4% of US invented patents were jointly owned by organizations in 1998/99 (Hicks & Narin, 2001).[i] Co-assigned patents are concentrated in biotechnology, pharmaceuticals and medical equipment, where they often involve public sector organizations jointly patenting with companies. In biotechnology, the small firm rate of joint patenting – 6% - equals that of large firms. In other technologies, where joint patenting is less common, the small firm rate of co-assigned patenting exceeds the large firm rate. Excluding biotechnology patents, 3.0% of small firm and 1.7% of large firm patents are co-assigned. Hagedoorn (2002) argues that co-assigned patents result from jointly conducted R&D on a small scale that perhaps only produced one or two patents making it difficult to split the intellectual property. Small scale joint R&D projects are transactions in the markets for technology, and so small firms' relatively greater involvement supports our argument.

Finally, Arora, Fosfuri and Gambardella recognize the extensive literature suggesting that large firms are long lived while doubting that companies set up to develop and sell a particular technology will live a long time. They propose three possible outcomes for small technology developers:

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[i] Calculated excluding unassigned patents and parent-subsidiary joint patenting for the largest patenting companies.

1. Succeed in becoming full-fledged manufacturing companies and grow large enough to exist for a long time;
2. Find that being good at developing a single technology does not make one well suited for developing future technologies; firm fails
3. Continue to develop new technologies

They consider the first unusual and the second and third equally likely. We would add to that list a fourth outcome, being acquired by a large firm looking to obtain the small firm's technology. Although we need more information on the probability of each outcome, note that an old small firm results from only one of the four possibilities. Thus we might expect few small firms to live long enough to acquire substantial patent portfolios and a relative dearth of older serial innovators.

We do not have the founding date for each firm, but we do have the first year in which each firm applied for a patent (for patents issued 1970 or later). So we can examine firm age as judged by the year in which the firm, or its predecessors or subsidiaries, made its first patent application. We classified firms according to the decade in which they applied for their first patent. Figure 1 displays the results. 43% of the small firms applied for their first patent after 1989, compared with 5% of the large firms. On the other hand, 58% of the large firms applied for their first patent in or before 1970, compared to 7% of the small firms. The small firms are young; the large firms are old.

***** Figure 1 here *****

Arora, Fosfuri and Gambardella (pp. 284-285) ask "might it not be more useful then to think of a firm as rising for a specific purpose, such as the development of a particular technology, to then be dissolved and its assets allocated elsewhere, once that purpose is accomplished? This would make these companies more similar to "projects" (possibly built around some intellectual property rights)." These data suggest that even projects that are comparatively technologically substantial and successful tend to run their course after 20 years.

### *Tradable technology*

We have argued that many small firms with substantial patent portfolios appear to specialize in developing technology, which is a viable business model when technology is tradable. We now shift perspective to focus not on firms, but on their technology. Compared to technology developed to be used in-house, we hypothesize that tradable technology has the following distinguishing characteristics:

1) Higher impact - high technological impact as measured by patent citations has been shown to be associated with high commercial impact. Technology with more commercial potential will be more tradable, or more attractive to buyers.

2) Broader impact - the broader the impact of an innovation on other technologies, the more interested buyers there are likely to be. Breadth of technological impact is likely to be related to size of market.

3) Broader based – to be marketable, an innovation must not duplicate the work of the larger firm customers. Technology that has less immediate precedents in its technology class is likely to be more radical innovation and should be more marketable.

4) More science linked – Arora et al (2002) argue that science provides the kind of systematic knowledge that underpins tradable technology. We would expect therefore that tradable technology will exhibit evidence of closer links to scientific knowledge.

The following sections will test for these characteristics of tradable technology by comparing the patent portfolios of small and large firms. The small technology supplier's existence depends on the technology market while technology licensing augments the R&D strategy of a large firm, serving as an adjunct rather than the purpose around which the firm's innovation is structured. Therefore, the technology of successful innovative small firms can be expected to be oriented to the requirements of that market. By comparing characteristics of small and large firm innovation we can uncover some of these requirements.

**High quality innovation**

The patents of small and large firms differ in average quality. A patent represents a contribution to technical advance of unknown magnitude. The size of a firm's patent portfolio has been found to be closely related to activity levels, that is to the size of R&D budgets. The value of a patent portfolio has been found to be less related to its size than to the importance of the patents it contains (Deng, Lev & Narin, 1999). Identifying high-value patents is necessary because the value of each patent varies enormously; a few patents are extremely valuable and a vast number are almost worthless. (That is, the value of patents is not normally distributed.) We measure the importance of patents using patent citations.

Citation rates vary by technology; therefore it is important to assess each patent's citation count in comparison to others in its technical field. Older patents also have more time to accumulate citations; therefore it is important to compare citation rates independent of the age of the patent. We use here a citation index that does both. For each patent, the value of the index is calculated by comparing its citation count against the citation counts of all patents issued in the same year and in the same technology area. The value of the index is 1 if the patent is cited as often as expected for a patent of that age in that technology area and is greater than 1 for patents cited more often than expected and less than one for patents cited less often than expected. The citation index averages 1.53 for small firm patents and 1.19 for large firm patents.[j] Small firms are thus more effective in producing high-value innovations.

This is most strikingly confirmed by examining the patents with the highest citation indices. Small firms account for 6% of the patents issued to the 1,071 most innovative firms. But when these patents are ranked by citation index, we find that small firms account for:

- 8% of the top 10%,
- 9% of the top 5%,
- 14% of the top 1%.

The small firm share of the top 1% most important patents is more than double their share of patents overall. Put slightly differently, 2.3% of small firm patents are found among the most cited 1% of patents produced by the 1,071 most innovative firms. Thus, a patent from a small firm is more than twice as likely to be found among the top 1% highest impact patents than is a patent from a large firm.

To explain this striking result, we might surmise that the internal systems to encourage patenting and the departments of patent lawyers maintained by large firms serve to raise the propensity of large firms to patent. That is, given a trivial innovation, staff at a large firm are more likely to pursue a patent than are staff at a small firm, who have better things to do. Puzzlingly enough, a large number of studies instead show that small firms consistently and significantly produce a higher number of patents per R&D dollar spent (see Cohen & Klepper, 1996a for a review). Analyzing this empirical observation, Schmookler (1966, p 33-35) noted that large firms do not patent all of their inventions since their better

[j] The index is calculated over the entire patent system including foreign firms, individual inventors etc. That patents from U.S. firms with more than 15 patents are on average cited more than expected is therefore reasonable.

market positions and financial resources provides them various means to fend off potential imitators. Many large corporations have a policy of commercially testing inventions in the market first, and abandoning them without seeking patents if they are unsuccessful. Hence it is likely many of the minor inventions of large firms remain unpatented as compared with those of small firms. For inventions of great commercial importance however, patenting is a necessary means of protecting intellectual property for both small and large firms.

The exact relationship between the distribution of patents and the distribution of underlying inventions, and how firm size moderates this relationship is indeed hard to empirically establish. However, both the arguments above suggest that the probability of a firm seeking a patent on its invention increases with the quality of invention for both large and small firms. Hence, by comparing patents at the right-end of the importance distribution (highly cited patents), we mitigate the potential for our conclusion to be biased by unobservable factors that impact the patenting propensity of large and small firms differently at the left (or trivial) end of the distribution.

To test this idea, we eliminated from consideration truly trivial patents by removing patents cited less than expected for their year and technology area. That is, we calculated the share that top 1% patents have of patents whose ratio of actual to expected cites was greater than 1. The result is the same; among patents cited at least as often as expected, small firm patents are twice as likely as large firm patents to be found among the top 1% of patents. Specifically, 5.3% of small firm patents and 2.3% of large firm patents with a citation ratio greater than 1 are among the top 1% most cited patents. In other words, the citation distributions of small and large firm patents differ, with small firm patents earning higher citations. This difference is greatest in the "right-tail" of the citations per patent distribution; for patents below the 75$^{th}$ quartile, the citation distributions of large and small firms appear increasingly alike.

Small firm innovations are more than twice as likely as large firm innovations to be extremely high impact. Small firm innovators are extremely effective at producing technically important innovations – and technically important innovations are most likely to be commercially important and hence licensed. Success as a technology vendor presumably requires high quality technology to sell. Thus we can interpret the small firm's technological excellence as a requirement for survival as a specialist technology supplier. The serial innovators are survivors among small technology-focused firms.

**<u>Generality of invention</u>**

Since we measured technological excellence using citations and since the small firms do not have enough patents to self-cite themselves to the top of the list, the high citation counts of small firms indicate a broad interest in their technology. Large firms may develop specific technologies of use only in their own processes – "local" technologies in the words of Arora, Fosfuri and Gambardella. Such advances might perhaps be significant and clever but without broader applicability are unlikely to be highly cited by others. A specialist technology supplier needs a broad market, and so needs to produce technology relevant to other firms. Such technology is likely to be more generic, related to the general-purpose technology (GPT) identified by several authors as facilitating the division of innovative labor in technology markets (Stigler, 1951; Bresnahan and Trajtenberg, 1995). GPTs are characterized by their potential for use in a wide range of sectors and by their technological dynamism. Developments in GPTs increase the productivity of R&D and trigger successive innovations in 'downstream' sectors (Bresnahan and Trajtenberg, 1995). GPT's are pervasive across sectors and industries, playing a key role in technical change and economic growth. Some of the most pervasive GPTs include the steam engine during the first industrial revolution, electricity during early 20$^{th}$ century and microelectronics during the last three decades (Helpman and Trajtenberg, 1996).

Technology suppliers face potentially very high fixed development costs. They will benefit from developing GPTs, even if the technologies are relatively modest in scope, because the efficiency of a technology supplier increases with the number of firms or sectors using its technology. Hence, the technology supplier's probability of success increases with the generality or the range of technology applications of the invention (Arora et al, 2001; p 143-146). Small firms specialized in supplying technology have incentives to develop GPTs that large firms do not since very few manufacturing firms are large enough to have the capacity to satisfactorily exploit such technologies in-house.

We would therefore expect the inventions of serial innovators to be more general than those of large firms. To test this hypothesis, we use a measure of generality proposed by Trajtenberg et al (2002) that is based on the extent to which citations received by a patent are spread across different technology classes. Citations dispersed widely across technology areas denote broader technological impact and hence greater generality of the invention[k]. The generality measure increases from '0' -- for a patent that receives all its citations from one 3-digit USPTO technology class -- to '1' for a patent whose citations are evenly spread across technology classes. We constructed the generality measure by collating citation information through 2002 for all patents in our database. Patents that had not received any citations were eliminated. 40,392 or 22.2% of large firm patents and 2777 (22.7%) of small firm patents lacked citations and were dropped from our calculations.

The first column of Table 1 presents the results of our simple Ordinary Least Squares (OLS) regression model. The generality index is regressed on a dummy variable that indicates whether the patent belongs to a small firm (serial innovator). Because the granularity of classification varies across technologies, we control for technology area by including a series of dummy variables. Year effects are

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[k] Trajtenberg et al (2002, p60) define the generality index as, $GENERAL_i = 1 - \sum_{k=1}^{N_i} \left( \frac{NCITING_{ik}}{NCITING_i} \right)^2$ where $k$ is the index of patent classes and $N_i$ is the number of different classes to which the citing patent belongs. In other words, the generality index is 1-Herfindahl Index of concentration. Trajtenberg et al (2002) use this to show that university patents are, on the average 15% more 'general' than non-university patents (years 1975-88).

also controlled for. We also include the number of citations received by the patent as a control since generality tends to increase with the number of citations (Hall, 2002). We find that patents belonging to small firms are about 14% more general than patents belonging to large firms on average (controlling for number of citations[1], time, technology effects). Additionally, the generality coefficients on technology class control variables (not shown here) suggest that technology areas like semiconductors, computers and telecommunications (which are viewed as GPTs) were more general than technology areas like heating and ventilation, agriculture, oil, natural gases and mining. This reassured us that the generality index is capable of capturing the breadth of impact of various technologies as anticipated by theory. We also found, by estimating within industry regressions, that small firm patents were significantly more general in chemicals (32% more general than a large firm patent), pharmaceuticals (17%), semiconductors (2.7%), telecommunications (6.8%) industrial machinery (29%), electrical appliances (21.4%) and office equipment (31.3%), controlling for patent year and citation frequency effects. These are among sectors identified by Arora et al (2001) as having well developed markets for technology.

As Bresnahan and Trajtenberg (1995) note, GPTs play the role of enabling technologies, rather than offering complete, final solutions. Inventions that are highly general are associated with greater social returns relative to private returns (Nelson, 1959). It is difficult for an inventor -- large or small -- to own all the complementary assets required to completely appropriate returns due to a GPT. However, Arora et al (2001) have argued that a division of innovative labor enables specialized technology suppliers such as our serial innovators to exist, and they can find it worthwhile to invest energies in innovations that are characterized by their broad technological impact because they can capture enhanced returns through technology trading. Our data seem to support this argument.

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[1] The coefficient on small firms was much larger when we estimated the regressions without controlling for number of citations. This suggests that the generality measure is positively correlated with citation frequency, and also that small firm patents receive more citations on average, a point made in an earlier part of the paper.

**Technological lineage**

Next, we examine patent references to prior art to investigate differences in the technological pedigree of small and large firm inventions. We argue that patterns in patent referencing suggest that small firm technology is more original, or less derivative, than large firm technology.

That small firm patents are less derivative is first illustrated by their tendency to reference more patents produced outside the firm and less patents produced inside the firm than large firm patents. Small firms may be forced to reference outside their portfolios by the smaller size of their portfolios. However, the point is worth checking because portfolio size might not be the deciding factor, rather it could be that the number of prior patents owned by the firm that are directly relevant to the current invention is more relevant to whether a patent references inside or outside the firm. A small focused firm may not be so different from a large firm in the number of directly relevant prior patents.

We constructed an index of the length of reference lists in the same way as the citation index was constructed except only patents in this study entered the calculation. For each year and each technology area we calculated the average number of references to other patents, excluding self-citation of patents from the same firm. This we call the "expected value". Then for each patent, we compared the number of patent references to the expected value for its year and technology area. We then calculated the average of these actual/expected ratios for large and small firms to obtain our index. Compared to large firms, small firms cite outside material 1.5 times as much. The outside-reference index values were 1.56 for small firms and 0.98 for large firms. Compatible with this interpretation is the finding that small firms reference fewer of their own patents. We calculated the number of self-citing references to prior patents we might expect on a patent in this set, given its broad technology area and year of issue. We find that small firm patents carry about 80% of the number of self-citations that large firm patents carry. The index values for self-citations to patents produced by the same company were 0.84 for small firms and 1.03 for large firms. Thus the technological innovation of small firms builds more heavily on developments outside the firm than does the innovation of large firms. Whether this follows simply from small size or not, it suggests a greater degree of novelty in small firm patenting than is present in inventions built more heavily on prior work inside the firm.

We pursue the idea that small firm patents are less derivative by examining referencing across technology areas. Trajtenberg et al (2002) argue that a patent referencing previous patents belonging to a broad spread of technology classes represents a synthesis of divergent ideas. Inventions associated with such patents are likely to be highly original and basic.

If serial innovators specialize in bringing broad based ideas to the technology marketplace, we would anticipate that patents assigned to serial innovators reference patents across a wide spectrum of technology classes. To test this expectation, we construct a measure of originality along the lines of the generality index with citations replaced by references. Depending on whether a patent references previous patents that belong to a narrow or broad set of technologies, the originality score will be low (close to 0) or high (near 1). Results of regressions of this variable on a firm size dummy, number of references made, technology class and year controls are tabulated in column 2 of Table 1. The average patent of a serial innovator scores about 6% higher on the originality index as compared to an average large firm patent after controlling for time, technology class and number of references made. The results are highly statistically significant[m].

A patent with high originality has less immediate precedents in its own technology class and represents a departure from traditional molds. Our results suggest that as suppliers of technology, serial

[m] Whether a 6% difference in the originality index amounts to a practically substantial difference is empirically hard to address. The median patent in our data achieved an originality score of 0.5. In comparison, a patent just making it to the 99th percentile of the index scored 0.36 higher. Contrast this with the 0.02 points (6%) difference (OLS coefficient reported in Table 1) between the originality scores of large and small firms.

innovators tend to specialize by drawing and synthesizing from a wide range of technologies outside the firm. Hence the resulting invention is less incremental and more idiosyncratic. This implication is consistent with earlier studies that view small firm innovations as more radical, breakthrough, major, and less cumulative as compared to large firms' (Pavitt and Wald, 1971; Scherer, 1991; Cohen and Klepper, 1996b; Yin and Zuscovitch, 1998). It may also reflect the strategic choice of innovative small firms to specialize in less crowded but increasingly fragmented technology niche markets (Carroll, 1985).

On the other hand for certain sectors and inventions a high value of originality can convey the additional meaning of a significant technology convergence. Arora et al (2001, p70) cite the example of biotechnology that draws from areas as diverse as genetics, information technology, software and robotics to foster innovations which in their turn breed applications in a vast array of fields. Hence, when coupled with our earlier findings about generality, the originality results serve to reinforce the status of serial innovators as having a unique and prominent role in the development of "general specialties" (Stigler, 1951).

**Science-linked innovation**

Arora, Fosfuri and Gambardella emphasize the importance of systematic knowledge for technology markets. Systematic or theoretical knowledge makes it easier to "unstick" knowledge from its local context through codification. Codified knowledge is much cheaper to move than uncodified knowledge. By reducing transaction costs, increased codification facilitates the emergence of technology markets. In addition, systematic knowledge with a theoretical component such as science provides is more generic and as such enables general purpose solutions to be developed that can be marketed broadly. "Advances in science mean greater ability to comprehend a wider set of previously unrelated phenomena within common explanatory frameworks, and this facilitates efforts to reduce the distance among them" (Arora, Fosfuri and Gambardella (AFG), p. 155). As discussed earlier, specialist technology suppliers have an advantage over large firms in developing GPTs or technologies with broad applicability. Arora et al, point in particular to the development of chemical engineering as a discipline as a prerequisite to the emergence of specialist engineering firms. They also place great weight on the science intensity of biotechnology facilitating technology markets in that area. Thus small specialist technology suppliers can be expected to innovate closer to the scientific frontier because that is where the broadly tradable technology opportunities are more likely to be found. We examine this in two ways, first share of references to university patents and second, extent of referencing from patents to scientific papers.

University inventions have been traditionally viewed as fundamental, abstract and embodying high scientific content (Dasgupta and David, 1994). Recent developments in areas like biotechnology have focused attention on the role of university-based entrepreneurs in commercializing university research (Zucker et al, 1998). University patents are characterized by their closeness to science and basic content. We argue that a patent that makes a high proportion of references to university patents or to scientific journal articles is rendered basic by association.

Serial innovators are distinguished from start-ups by their persistent record of innovations. Yet we find evidence that serial innovators continue to depend on fundamental technologies provided by universities. The case of Pharmacyclics, Inc. exemplifies our point. The firm was founded by Jonathan Sessler and Richard Miller in 1991 and was conceptualized during the period when Miller was treating Sessler's cancer at the Stanford University Medical Center. The firm develops therapeutics based on ring-shaped small molecules called texaphyrins that when present in diseased tissue make other therapies, such as chemotherapy, more effective. Pharmacyclics licenses the texaphyrin technology from the University of Texas. This Sunnyvale, California based firm of 120 people owns 31 patents (issued between 1996 and 2000, www.pharmacyclics.com April, 2004). Pharmacyclics patents are high impact, 39% (12 patents) are among the top 10% most cited patents in their technology areas. Finally, Pharmacyclics patents on average reference university patents about half the time.

While not all serial innovators have such a spectacular history of development or strong university links, our results do show that serial innovators reference a high proportion of university patents in comparison to large firms. Results of regressions of citations to university patents on a firm size dummy, number of references made, technology class and year controls are tabulated in column 3 of Table 1. The average patent of a serial innovator references university patents about 33% more often than the average large firm patent after controlling for time, technology class and number of references made[n]. The results are highly statistically significant.  This nearness to inventions of a fundamental nature allows serial innovators to specialize in providing intermediate technology inputs to larger manufacturing firms.

***** Table 1 here *****

This point is supported by examining patterns of referencing to the scientific literature. Increasingly, patents are citing non-patent documents as prior art, and many of these are papers in scientific journals (Narin et al. 1997). Patents that reference many scientific journal articles are different from patents that reference none. For example, a patent on a genetically engineered seed, or on a neural network based process control may reference ten or more scientific articles. In contrast, an improved design for a part of a motor may reference none.  High science linkage indicates that a company is building its technology based on advances in science.

We find that the science linkage of small firm patents is stronger than that of large firm patents. The lists of references to scientific journal articles on small firm patents are more than twice as long as expected given how much literature large firms reference.  We calculated a science linkage index in the same way as the outside patent reference index. We find that the science linkage index for small firms is

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[n] The average patent does not cite university patents, while the most a patent in our dataset cited university patents was 34 times.

2.55 and for large firms is 0.90. Here we see a rather large difference between the behavior of small and large firms.

Since our indicator was normalized by technology area, we are not repeating the finding that small firms innovate in science intensive areas such as biotechnology. The small firms are more science intensive even when innovating in traditional technology areas. E. Khashoggi Industries is one such case. About 10 years ago, Khashoggi began a line of patenting in manufacturing and molding from sheets of inorganically filled organic polymer matrix. These patents are classified into technologies that average less than two references to scientific material per patent; areas such as polymers, miscellaneous machinery and miscellaneous manufacturing. The Khashoggi patents carried 20 to 40 references to scientific literature. Mr. Khashoggi has subsequently established a firm called EarthShell (listed on the NASDAQ) which has exclusive licenses to the patents of E. Khashoggi Industries. EarthShell commercializes composite material technology for the manufacture of foodservice disposable packaging. This packaging is not just biodegradable but is super environmentally friendly, being a composite of ground limestone and potato starch. Khashoggi Industries itself is a very obscure company that may well be a research firm built around the Edisonian figure of Essam Khashoggi.

Our quantitative analysis establishes that Khashoggi is not alone, and that we have identified a specialist technology supplier niche - pursuing a traditional technology with a research-intensive approach. The indicators suggest that many of the serial innovators may take this approach. Geobiotics for example, develops microorganisms to recover metals and patents in metals technology, referencing far more scientific literature than the standard metals patent. Similarly, Optex Communications (with patents in telecommunications), a firm that worked with money from the Advanced Technology Program (ATP) of the U.S. National Institute of Standards and Technology (NIST) to develop memory devices using electron trapping materials, or materials that can store electrons in a stable electronic state for long periods after they have been excited by incident light. Both firms have far more science-intensive patents than the large firms working in their technology area.

**Extreme referencing and technology trading**

Small firm reference lists are more extensive, both lists of scientific papers and non-self-cited patents. This, we argue signifies technology that is more broadly and scientifically based and more tradable therefore. There is an interesting variant of this phenomenon that merits examination in its own right. Among the small firms we find “extreme referencers” whose patents list pages of references. It seems unlikely that many firms explicitly strategize over reference lists on patents. Such extreme referencing we believe arises in those few firms who do, whose patent lawyers make an explicit link between reference lists and technology trading of a particularly confrontational and controversial kind. Such outlandishly long reference lists are thought to make patents stronger in court, and technology suppliers who anticipate facing litigation need especially strong patents.

Take the example of Ronald A. Katz Technology Licensing LP patenting in telecommunications. “Telephonic-interface lottery-system” and “Telephonic-interface statistical analysis system” are two patent titles favored by R.A. Katz. Of the 15 R.A. Katz patents issued 1996-2000, five list over 60 references to scientific literature, in a technology where the average patent lists less than one. R.A. Katz Technology Licensing LP is something of a “pure play” in the technology market whose business model is to use these patents to extract $2 billion in patent licensing revenue from large firms (such as AT&T, American Express, IBM, Microsoft and Wells Fargo ).

This strategy is controversial as it is seen to be based less on inventing key technology than on making patents so complex that firms settle rather than wade through the patents to prepare for litigation. The patents contain hundreds of pages of claims, each slightly different from the others. An attorney is quoted in Forbes ASAP as saying: “He has literally thousands of claims, and they differ only in trivial respects. Many are broad and vague, and sorting them out takes a lot of time.”

The 60 references to scientific literature (and over 300 references to other patents, and over 300 references to other non-patent material) on each patent also serve to make each patent more difficult to challenge legally. Any challenger must grapple with the contents of all of the references, and it is very difficult to use any of the referenced material as evidence that the patent should not have been granted because the invention was not novel. The patent office examiner is presumed to have examined all the referenced material and to have judged the invention novel in light of it.

> *Time, particularly when lawyers are involved, means money. When faced with a large number of complicated patents, it's cheaper for companies to pay for a license than to hire expensive attorneys to figure out their merit explains longtime patent system critic Greg Aharonian, publisher of Internet Patent News Service. Companies, he says, end up paying Katz to leave them alone. And perhaps to save money, all four companies that found themselves in court with Katz settled before a final court judgment on the validity of the patents. (Pfeiffer, 2002)*

The extreme nature of the Katz reference lists is unusual, but not unique. InterDigital Communications lost money for many years designing, manufacturing and selling complete wireless phone systems primarily for rural areas. They never could get big enough to finance and support major installations. And many poor countries in need of the systems lacked funds to pay for it. Its new strategy is to earn the bulk of its profits from licensing patented technology to large companies that can provide the financing and in-country presence needed to capture profitable 300,000-line contracts. So InterDigital has moved into technology development and away from making, selling and servicing complete wireless telephone systems.

Coincident with InterDigital's shift in strategy was the appearance of 20 or more science references on some of its patents. This came after a 1995 jury verdict against InterDigital in a patent-infringement lawsuit that it had filed against Motorola. The heavier documentation is part of its new worldwide licensing strategy. InterDigital's general counsel said: "Our patents now use volumes of scientific research papers, journal articles, and other patents to establish the state of the art at the time of our invention. When you take that kind of patent to a prospective licensee, they are impressed" (Holcomb, p. F7).

Extreme referencers seem to be aggressive technology traders with a conscious referencing strategy directly linked to technology trading. A patent protecting a technology that may face litigation needs to withstand intense scrutiny from large companies who would rather not pay. Heavy referencing, along with other characteristics of the patent document, may help strengthen patents in anticipation of legal challenges. A patent representing an invention with application only within a firm's own technology will never be so exposed as it nestles among other protections including a pool of patents, trade secrets and complementary assets. The applicant framing such a patent with no intention of trading it need not spend more money to devise an "extra-strength" patent.

## Conclusions

In essence this paper argues that Edison lives. The inventor-entrepreneur epitomized by Thomas Edison was said to have died out with the advent of large corporate laboratories. The complexity and scale of modern technology were thought to preclude that type of activity. Arora, Fosfuri and Gambardella point to studies detailing how independent inventors early in the century were enticed into corporate laboratories by the need for financial security. Clearly modern technology is complex, and the truly independent inventor remains marginal. The inheritors of the Edisonian tradition lead firms with perhaps several hundred employees bringing together the specialists and equipment needed to pursue economically valuable innovation in the most advanced technology.

However, there are certain prerequisites. Stigler (1951) argued that increasing innovative division of labor allows specialist technology suppliers to exist. Arora, Fosfuri and Gambardella build on this to note the importance of general purpose technologies in markets for technologies. We find evidence that successful specialist technology suppliers produce high quality technology and more general purpose technology (GPT) that is broadly applicable - evidenced by citation across many technology areas – and less derivative technology – evidenced by its broad technology base and close links to science. That we find evidence of specialist technology suppliers in patent data, and indeed evidence that some work to produce “extra strength” patents, suggests that well defined intellectual property rights provide a strong incentive for small innovative firms to actively patent their inventions and become specialist suppliers of intermediate technological inputs. Visible success in such markets – firms living on consulting, licensing and then getting rich in a buyout – will attract resources such as venture capital and more entrepreneurs willing to take the risk. In this way innovators are able to establish and maintain small firms to pursue their ideas outside large corporations.

Specialist technology suppliers bring to the economy diversity in innovative approaches and risk sharing that encourages a faster pace in innovation. In its implications for industry structure, our paper calls for a reexamination of linear theories of firm growth dynamics that view large size as a natural outcome of industrial small-firm survival and success. Markets for technologies help explain the presence of long lived, highly innovative small firms, which is an empirical reality. The focus of our effort has been to clarify the sources and nature of inventive activity in such firms.

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**Figure 1: Small firms are younger**

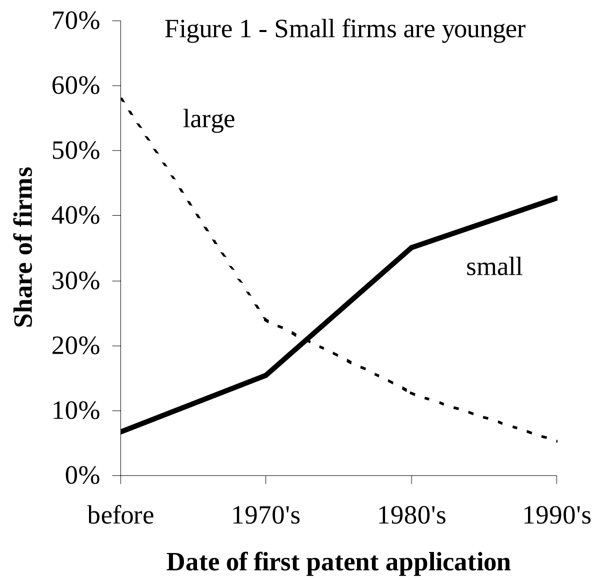

**Table 1: Small firms, generality, and technology antecedents**

| | General | Original | University references |
|---|---|---|---|
| Small-firm | **0.02** | **0.02** | **0.33** |
| | [0.00]*** | [0.00]*** | [0.02]*** |
| Citations | 0.011 | | |
| | [0.000]*** | | |
| References | | 0.004 | 0.016 |
| | | [0.000]*** | [0.000]*** |
| Constant | 0.18 | 0.44 | -0.1 |
| | [0.01]*** | [0.01]*** | [0.02]*** |
| Observations | 150802 | 189973 | 189973 |
| R-squared | 0.17 | 0.1 | 0.18 |

Robust standard errors in brackets. Estimations control for technology class and year effects.

*** significant at 1%