NBER WORKING PAPER SERIES

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Working Paper 30354
http://www.nber.org/papers/w30354

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
August 2022

We thank Sharon Belenzon, Scott Rockart, Sharique Hasan and Daniel P Gross for their useful feedback. We also thank all seminar participants at the strategy seminar series at Fuqua School of Business for their thoughtful comments. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

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NBER Working Paper No. 30354
August 2022
JEL No. O31,O32,O33,O34

ABSTRACT

Do large firms produce more valuable inventions, and if so, why? After confirming that large firms indeed produce more valuable inventions, we consider two possible sources: a superior ability to invent, or a superior ability to extract value from their inventions. We develop a simple model that discriminates between the two explanations. Using a sample of 2,786 public corporations, and measures of both patent quality and patent value, we find that, while average invention value rises with size, average invention quality declines, suggesting, per our model, that the large firm advantage is not due to superior inventive capability, but due to the superior ability to extract value. We provide evidence suggesting that this superior ability to extract value is due to greater commercialization capabilities of larger firms.

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A data appendix is available at http://www.nber.org/data-appendix/w30354

1 Introduction

Stimulated by concerns over a decades-long increase in market concentration in the U.S. economy, the question of the existence of a large firm advantage in technical advance has reemerged in recent years (Autor, Dorn, Katz, Patterson and Van Reenen, 2020; Gutiérrez and Philippon, 2019). Yet, despite decades of research (Cohen, 2010), the source of a firm size advantage in innovation remains unresolved. Moreover, important policy implications are at issue. For example, if size provides an advantage in innovation, then, antitrust considerations aside, should policymakers be unconcerned as firms grow very large?

In this paper we ask: If large firms have an advantage in innovation, is it because they are better at invention or because they are able to extract more value from their inventions?[1] We develop a model whose predictions discriminate between an inventive capability and a value-capture advantage of size. For either advantage, the model predicts that the average private value of a firm's inventions should increase with firm size. However, average invention quality should increase with size if large firms are more capable inventors, but decline with size if they have a value-capture advantage. We empirically test these predictions with simple descriptive regressions and non-parametric analyses using data on publicly traded U.S. firms for the period 1980-2015.

Our paper contributes to the literature on the sources of the firm size advantage in innovation. Our principal contribution is to clarify two potential types of advantage and distinguish between them empirically using patent based measures of invention value and quality.[2] We find that average invention value increases with size, whereas average invention

[1] Coad, Mathew and Pugliese (2020) argue that firms differ in their ability to benefit from innovation and, thus, some firms do not invest in R&D. We distinguish between the ability to invent and the ability to commercialize and capture the benefits from inventions. Further, whereas Coad, Mathew and Pugliese (2020) focus on the extensive margin, we focus on the intensive margin of how much firms invest in invention.

[2] The term "patent quality" is occasionally used interchangeably with patent value (e.g., Higham, De Rassenfosse and Jaffe, 2021; Lanjouw and Schankerman, 2004; Kogan et al., 2017), as well as with "patent validity" (e.g., Lei and Wright, 2017; Frakes and Wasserman, 2017). Our results suggest that, though related, the concepts of patent value and quality are quite distinct. See, for example, Figure 2 below. We measure the technical quality of a patent with forward citations on the assumption that inventions of higher technical quality will induce others to patent similar or follow-on inventions.

quality declines with size, suggesting that large firms benefit mainly from an appropriability advantage. Using a new non-parametric test, we provide additional evidence that large firms do not have superior inventive capabilities by comparing their highest-quality inventions with those of small firms. These results are consistent with the size advantage arising not from superior inventive capability, but instead from the greater capacity that large firms have in capturing value from their inventions.

We subsequently consider commercialization capabilities as the source of large firms' appropriability advantage by exploring how markets for technology and markets for commercialization capabilities moderate the relationship between firm-size and private value and quality of inventions. Where access to commercialization capabilities is less tied to size, the links between value and quality, respectively, and firm size are weakened. For example, in industries where technology licensing or patent reassignments are common, the relationship between firm size and quality is weaker. Similarly, in industries where "markets for commercialization capabilities" are more pervasive, the relationship between firm size and quality also weakens because inventing firms need not rely only on internally developed commercialization capabilities to derive value from their inventions. These findings are consistent with the appropriability advantage arising from the greater commercialization capabilities possessed by large firms.

Section 2 below discusses the prior literature and provides conceptual background. Section 3 considers whether the source of the large firm advantage resides in large firms' ability to capture value or their inventive capability. Section 4 addresses the source of large firms' apparent appropriability advantage. Section 5 presents additional non-parametric results on the relationship between firm size and inventive capability. Section 6 provides robustness tests and Section 7 concludes the paper.

2 Background and literature

Firms' R&D expenditures are closely related to their size; among R&D performers, R&D increases monotonically and typically proportionately with size within industries. The proportionate relationship was interpreted initially as indicating that large firms had no advantage in R&D, and perhaps a disadvantage because R&D productivity appeared to decline with size (Scherer, 1991). Cohen and Klepper (1996) showed, however, that the proportionate relationship reflected an advantage to size, such that large firms earned a higher return per R&D dollar than small firms.[3] However, by assuming all firms were equally capable at invention, they never addressed the question of the relationship between firm size and inventive capability.

It is plausible that firm size is associated with superior inventive capability. First, large established firms should be able to attract the high quality personnel that are essential to such capabilities (Vinokurova and Kapoor, 2020; Kerr and Lincoln, 2010). With deeper pockets, they can offer higher pay (Popkin, 2019). They can also offer greater job security (Sauermann and Roach, 2018) and more opportunities for promotion (Bennett and Levinthal, 2017). Moreover, they can offer more of the resources that would attract talented candidates, including better equipment, access to data, as well as the prospect of working with other talented technologists. In related work, Coad, Segarra-Blasco and Teruel (2020) find that large firms are more likely to invest in basic and applied research, in addition to technological development. Insofar as research leads to higher quality inventions, this is consistent with large size being associated with higher inventive capability.

Cockburn and Henderson (Henderson and Cockburn, 1996; Cockburn and Henderson, 2001) provide evidence on advantages to scale in invention using detailed data for ten pharmaceutical firms at the R&D program (i.e., therapeutic class) and project levels. Using

[3] Cohen and Klepper (1996) argued that a higher return to their R&D induced larger firms to profitably undertake more incremental R&D projects, thus yielding what only appeared to be a decline in R&D productivity. Such an apparent decline would even occur if one assumed large and small firms were equally efficient in their R&D. See Knott and Vieregger (2020) for a complementary perspective on the reconciliation of this seeming paradox.

"important" patents granted from 1960 through 1988 as their dependent variable, Henderson and Cockburn (1996) find evidence of benefits of scale and scope in drug discovery research.[4] For the same sample of firms, Cockburn and Henderson (2001) use New Drug Applications (NDA's) at the project level to test for scale and scope benefits in drug development. While they find no evidence for benefits of scale in development, they find evidence consistent with advantages of large scope, measured as the number of therapeutic classes or "programs" in which the firm is active. By not including a measure of overall firm size in their analyses, Cockburn and Henderson do not, however, address firm size advantages that would apply to either firms' research or development efforts.

Indeed, large firms may actually be disadvantaged in their abilities to invent. Greater size, for example, may undermine inventive capabilities to the degree that more bureaucracy and hierarchy stifle new ideas (Schumpeter, 1942; Sah and Stiglitz, 1986, 1988). Also, agency or coordination costs increase with size, and the managerial function itself may be subject to diminishing returns (Holmstrom, 1989). Talented scientists may also have preferences to work for small, more entrepreneurial firms (Sauermann and Roach, 2018). Thus, given the absence of empirical results on large firms' inventive capabilities, the question of the link between firm size and inventive capability remains unresolved.

Cohen and Klepper (1996) argue that a large firm can extract more value from an invention by selling more output embodying the invention. This argument is based on two related assumptions. The first is that current output conditions expectations of future output.[5] The second assumption is that firms profit from their inventions by embodying them in their own

[4]Important patents are defined in their study as patents issued in at least two of the three major patent jurisdictions of the USPTO, Europe's PTO, and Japan's JPO.

[5]While consistent with the common assumption of convex adjustment costs in the theoretical literature on growth and investment, Cohen and Klepper (1996)'s justification for this assumption is largely empirical, notably that growth rates tend to be modest (Hart and Prais, 1956; Singh and Whittington, 1975; Evans, 1987). Cohen, Lee and Walsh (2021) report that most new products tend to have incremental effects on sales. Their survey findings indicate that, for most manufacturing firms, the most important product innovation (i.e., that new product accounting for the most revenue) accounted for 10% or less of their sales during 2009. Moreover, most innovations are imitated in less than three years (Levin et al., 1987), allowing little time for significant capacity expansion.

output.[6]

The embodiment assumption appeals to both theory and empirical findings. Arrow (1962) argued that markets for inventions in disembodied form (i.e., descriptions) will tend to fail. Survey research shows that most manufacturing firms protect profits from inventions through first mover advantages, secrecy, and the use of complementary capabilities (e.g., marketing, sales, manufacturing), all of which are implemented through a firm's own sales (Levin et al., 1987; Cohen, Nelson and Walsh, 2000).[7]

Cohen and Klepper's assumption that current sales of a firm's products are closely related to future sales raises the question of what capabilities enable firms to achieve a given level of sales. Teece (1986) suggests that it is a firm's complementary capabilities or assets that enable firms to commercialize, and thus realize new sales from their new products and processes. The resource-based view also emphasizes the importance of firm-specific capabilities as a source of competitive advantage (Peteraf, 1993; Wernerfelt, 1984; Barney, 1991; Makadok, 2001).[8] Teece (1986) also ties firm size to the critical role of complementary capabilities. He states, "Large firms are more likely to possess the relevant specialized and co-specialized assets within their boundaries at the time of new product introduction. They can therefore do a better job of milking their technology, however meager, to maximum advantage." (p. 301) Ceccagnoli and Rothaermel (2008) also suggest that such capabilities are close correlates of firm size, largely because they underpin growth due to innovation.

For concreteness, we shall refer to complementary capabilities as simply commercialization capabilities. Such capabilities span a variety of functions within the firm, including product development, manufacturing, marketing (e.g., brand) and sales (e.g., sales and distribution channels, and relationships with customers), that allow firms to capture more

[6] This is consistent with Schumpeter's (Schumpeter, 1942) argument regarding large, monopolistic firms when he states, "They largely create what they exploit." (p. 101)

[7] Consistent with this, Coad and Grassano (2019) show that firm size, rather than profitability or market capitalization, "granger causes" R&D investment.

[8] Survey research confirms that complementary capabilities are among the key means through which firms profit from their new products and processes (Levin et al., 1987; Cohen, Nelson and Walsh, 2000).

value from their inventions.[9] While some of these capabilities, such as brand and distribution, increase demand for a firm's products (Christensen and Bower, 1996; Rosenbloom, 2000), others, such as manufacturing or supply chain capabilities reduce the firm's cost of production (Filippetti and D'Ippolito, 2017).

The argument that large firms realize an advantage from possession of commercialization capabilities also depends on the embodiment assumption. If firms can readily license or sell the rights to their inventions to other firms, then they can realize returns to their inventions by capitalizing upon other firms' commercialization capabilities rather than their own. In our empirical analysis, we test whether the relationship between size and both invention value and quality weakens in those industries where inventions may be readily licensed or sold.

That a firm's commercialization capabilities importantly drive their sales of and profits from new products and processes strengthens the theoretical foundation for Cohen and Klepper (1996)'s second assumption that future sales embodying new products are closely related to current sales. One only needs to believe that expansion of firms' commercialization capabilities is subject to costly, time-consuming frictions. Commercialization capabilities that are firm-specific are particularly subject to such frictions because they require integration with the firm's other activities, including its product development and other functions. In contrast, where commercialization capabilities are more readily acquired via market transactions–possibly because they are more generic (i.e., less firm-specific) and contractable–those capabilities can be accessed much more quickly and at a lower short-run cost. Thus, when such capabilities are contractable, the firm's sales of a new product should be less tied to its existing capabilities, and, in turn, its sales prior to the development of the new product.[10]

A recent survey by Arora, Cohen and Walsh (2016) suggests that there is indeed a

[9]Note that we distinguish invention from innovation, where the latter refers to the commercialization of the former.

[10]Even where commercialization capabilities can be purchased, however, firm size may matter if the cost of finance declines with size.

relationship between the market for commercialization capabilities (MFC) and sales due to new products. The survey asked respondents to report the percentage of sales due to their most important new product innovation in 2009, and if its commercialization required the acquisition of new types of equipment or the hiring of personnel with skills different from those of existing employees.[11] We interpret a higher incidence of the latter as indicating that at least some commercialization capabilities can be readily acquired via market transactions in that industry–that MFC are more pervasive. In such industries, we would expect to see short-run growth of sales of new products to be greater. Indeed, Cohen, Lee and Walsh (2021) find that, for the 32 manufacturing industries in the sample, the correlation between the average percentage of sales of the firm's most important new product in 2009 and the percentage of firms acquiring these capabilities is 0.51. This strong relationship suggests that, in industries where commercialization capabilities are more readily procured, sales of new products will be less constrained by current capacity. Under such circumstances, we would expect a weaker link between firm size and, respectively, the value and quality of the firm's inventions.

To summarize, we expect firm size to be less closely tied to average invention value and quality when there are well-functioning markets for the output of inventive activity (i.e., markets for technology) or when there are well-functioning markets for the inputs required to commercialize firms' new products. While the prior literature (Cohen and Klepper, 1996) has explored the impact of markets for technology (MFT) on the firm size-R&D relationship, the impact of MFT on the relationship between size and either invention value or quality is less explored. What is entirely unexamined is how markets for commercialization capabilities (MFC) condition the size advantage of firms.

[11] Importance was defined as that product accounting for a plurality of sales in a given, identified market.

3 Value capture versus inventive capability

This section is comprised of several parts: a model, a description of the data and variables employed throughout the paper, and non-parametric and regression results testing the model predictions. We first confirm that large firms indeed realize greater private value from their inventions, and then consider whether the source of this value premium originates from a superior ability to capture value or from superior inventive capability, defined as an ability to invent higher quality inventions.

3.1 A model of returns, innovation, quality and firm size

3.1.1 Model setup

We construct a simple model of investment in invention building upon Cohen and Klepper (1996). Firms are price takers and make independent decisions on how much to invest. Recalling that we distinguish invention from innovation, rents are realized from inventions that, with subsequent investment in commercialization (i.e., development, manufacturing, marketing and sales), yield innovations in the form of either new products or processes (i.e., innovations). Rents accrue only in one period, after which the innovation is imitated. The firm faces an increasing marginal cost of invention, and there are no fixed costs in their production.[12] For the moment, we also assume that firms profit from their inventions exclusively by embodying them in their own output, s, which we treat as a measure of firm size.

The set of projects available to firm i is arranged in a decreasing order of technical quality (henceforth, simply "quality"), which refers either to the extent of product performance improvements for inventions leading to product innovation, or to cost reduction for those leading to new processes. The quality of the n^{th} project is $q(n) = A - bn$, so that marginal quality declines with the number of projects. We assume quality reflects the social value of

[12] Adding fixed costs would imply an additional restriction on the optimal number of projects in order to ensure that the firm breaks even. Doing so does not substantially alter the results of the model.

an invention, and we represent this total value as $Q(n)$. Let v represent the share of value that the firm appropriates from its inventions, i.e., $0 < v < 1$. The firm's optimization problem is to choose the number of inventions, n, that maximizes profits from inventions: $\max_n\{\pi = vQ(n) - d\frac{n^2}{2}\}$, where $vQ(n)$ represents total revenue net of the costs of commercialization, d represents the cost of invention, and $Q(n) = An - b\frac{n^2}{2}$.

The optimal number of projects, n^* is given by equating marginal revenue to marginal cost i.e., $vq(n) = dn$, which implies that $n^* = A\dfrac{v}{d + bv} = \dfrac{A}{b + \frac{d}{v}}$. It is easy to see that n^* increases with A and decreases with $\frac{d}{v}$.

With s representing firm size, the appropriability advantage can be represented as $\frac{\partial v}{\partial s} \geq 0$. One way to capture an inventive capability advantage to size is to assume that large firms have a higher value of A that increases the quality of all their inventions. That is, if $\frac{\partial A}{\partial s} > 0$, there is a size premium due to greater inventive capability.

Finally, note that average quality is simply $A - b\frac{n}{2}$ and average value is $vA - bv\frac{n}{2}$. Evaluated at n^*, it is straightforward to see that average quality and average value both increase with A. A higher value of A shifts the marginal quality schedule out, which implies that the average quality of inventions will be higher, as will their average value.

Whereas average value increases with v, average quality, however, declines. Recall that n^* increases as v increases. A greater ability to capture value from an invention implies that the firm has an incentive to produce more inventions. Because additional projects are of lower quality given diminishing returns, the quality of the average project will also be lower if v is higher.[13] The implications for how the two different sources of the size premium relate to average value and quality follow directly and are summarized in Table 1. Appendix A provides a formal proof.

Illustrating the intuition, Figure 1 shows a firm's marginal quality of invention schedule, $q(n)$ on the top panel, and corresponding marginal value–or, equivalently, marginal revenue–curve on the bottom panel. For the figure, we will also assume a constant marginal cost of

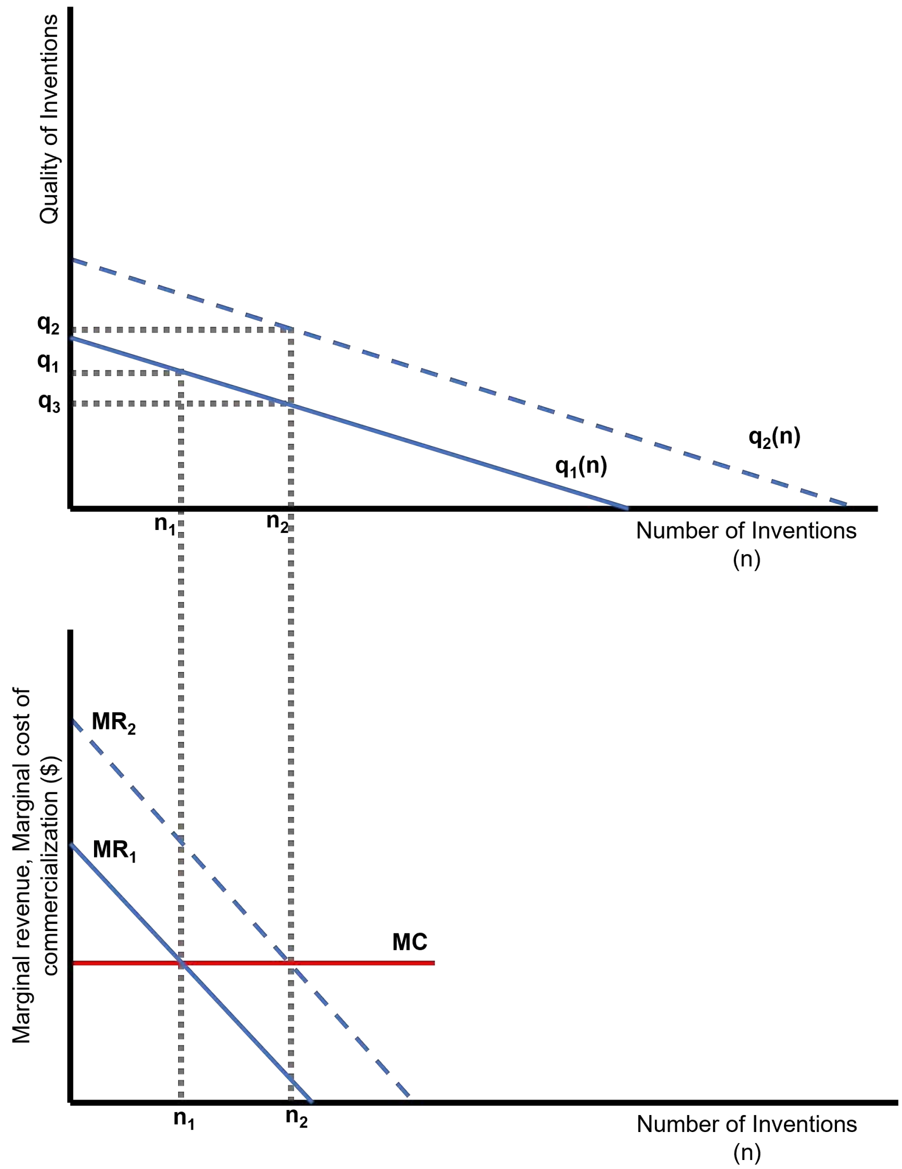
[13]The argument is symmetric to a reduction in the marginal cost of projects, d. As marginal cost falls, the value of the marginal project must also be lower.

invention. The firm's marginal private value from its inventions is the product of $q(n)$, and the share of value captured, v. Thus, the marginal revenue curve, MR_1, may shift to MR_2 either as appropriability, v, increases, or as a firm's inventive capability–reflected in $q(n)$– increases. The latter results from the outward shift of the quality schedule, $q(n)$, while the former occurs with no change in the quality schedule. But, as MR_1 shifts to MR_2 for either reason, the firm's marginal and, in turn, average private value of inventions increase, and the firm will increase the number of inventions it produces from n_1 to n_2. But, importantly, as shown on the upper panel, as marginal revenue shifts outward to MR_2 due to the shift in the quality schedule from $q_1(n)$ to $q_2(n)$, the quality of the firm's n_2 inventions will increase to q_2 from an initial value of q_1. In contrast, if the marginal revenue schedule shifts out due to an increase in value-capture, v, the quality of the firm's n_2 inventions declines to q_3, reflecting a downward move along the existing quality schedule. Thus, an increase in private value will drive the number of inventions produced, but the quality of those inventions will either increase or decline depending on whether that change is due to a firm's changing inventive capability or a change in the firm's ability to extract value from their inventions.

Prediction 1: If the size premium is due to superior inventive capability, we must observe a positive relationship of firm size with average private value and quality of inventions.

Prediction 2: If the size premium is due to superior appropriability, we must observe a positive relationship of firm size with average private value of inventions but a negative relationship between firm size and average quality.

Figure 1: Visualizing Model Predictions



Notes: The top panel of this figure plots marginal quality curves $q_1(n)$ and $q_2(n)$ on the y-axis and the number of inventions on the x-axis. The bottom panel of this figure plots the marginal revenue curves MR_1 and MR_2, and the constant marginal cost of invention curve MC on the y-axis and the number of inventions on the x-axis. MR_1 may shift to MR_2 for two reasons. With higher inventive capability (as shown in the upper panel), $q_1(n)$ shifts to $q_2(n)$ and firm produces n_2 inventions, where the marginal quality of the n_2 is q_2. Second, with higher appropriability (not shown), firms will also produce n_2 inventions, but the marginal quality of n_2 is lower, at q_3.

Table 1: Comparative Statics Summary Table

	Inventive Capability (A)	**Appropriability (v)**
Average Quality	Positive	Negative
Average Private Value	Positive	Positive

Notes: This table summarizes the results from comparative statics of average private value and average quality with respect to inventive capability and appropriability.

3.2 Data and variables

Our sample consists of 26,468 observations at the firm-year level. It includes 2,786 firms and spans years 1980 through 2015. The firms in our sample are manufacturing firms, in the SIC code range of 2000 to 3999.

To construct the sample, we extract a list of patents owned by US-headquartered public firms from Duke Innovation & SCientific Enterprise Research Network (DISCERN) (Arora, Belenzon and Sheer, 2021). Then, for each patent, we add a measure of invention value from Kogan et al. (2017) and a measure of invention quality (the number of forward citations normalized by mean citation count within each CPC class-grant year pair) from PATSTAT maintained by the European Patent Office. Furthermore, we add the grant year and primary CPC (Cooperative Patent Classification) code of each patent from patentsview.org maintained by the USPTO.

In the main specification, we aggregate the data to the firm-year level by averaging both invention value and quality for each firm and year, based on the patent application year. We also add firm sales for each year along with other accounting measures and industry code (i.e., SIC) from Standard & Poor's CRSP/Compustat database. We also present estimates at the technology area level in Appendix Tables C.5 and C.6.[14] See Table 2 for an overview

[14]In unreported analysis, we also conduct a patent level analysis, where the estimates can be thought of as the results of firm-level estimates where firms are weighted by the number of patents. That is, patent level estimates implicitly place a larger weight on larger firms. We avoid giving larger firms a higher weight by including technology area level analysis.

of variables and their corresponding measures used in this paper. (See appendix B for additional details on sample construction.)

3.2.1 Private value of an invention

We use two measures of private value. Following Feng and Jaravel (2020) and Kline et al. (2019) among others, we use patent values from Kogan et al. (2017), who estimate the private value of a patent using an event study that captures abnormal market returns within a three-day window in response to a patent issuance. We interpret these estimates as reflecting the private value of the patent to the firm. To derive the average value of a firm's inventions for a given year, we divide the total value of the firm's patents in a given year by the total number of patent applications filed by the firm in the same year.[15]

As an alternative measure, we use the share of inventions patented in multiple jurisdictions (Putnam, 1996; Lanjouw and Schankerman, 2004).[16] [17] Given that an applicant has to incur additional costs to file a patent application in more than one jurisdiction, the share of inventions patented in multiple jurisdictions should be related to the expected private value of the underlying invention. We construct this measure by identifying patent families of a firm's patents for each year and finding the share of those families with patents in multiple jurisdictions. To the extent that the share of inventions patented in multiple jurisdictions reflects the private value of an invention, we expect it to have a positive relationship with firm size. Both measures yield a similar pattern of results.

[15] Measuring patent value with an event study comes with its disadvantages. (Arora, Belenzon and Dionisi (2021) also note these limitations.) For instance, this approach can be sensitive to the time window selected, as a narrow window might not allow for sufficient time to capture market's response in full while a broad window might increase the chances of introducing market's responses to other events.

[16] A patent applicant typically has two options for pursuing patents in multiple jurisdictions for a given invention. First, the Paris Convention agreements allow patent applicants twelve months from the date of the first filing to seek patents in other jurisdictions. Additionally, an applicant may file a PCT (Patent Cooperation Treaty) application, which provides thirty months for the applicant to seek patents in multiple jurisdictions.

[17] We tested the possibility that the share of inventions patented in multiple jurisdictions is related to size due to large firms' superior access to finance by including cash flow as a control. The coefficient estimate was unchanged.

3.2.2 Invention quality

Assuming that a patented invention will induce others to invent similar or follow-on inventions when it is of higher technical quality, our proxy for the quality of invention is the number of forward citations received by each patent (Trajtenberg, 1990; Gambardella, Harhoff and Verspagen, 2008; Hall, Jaffe and Trajtenberg, 2005; Lanjouw and Schankerman, 2004). This can be thought of as a forward looking measure of quality. To account for systematic differences in citation behaviors across technology areas and to address concerns around truncation for patents in the latter years of our sample period, we normalize the number of forward citation by the mean citation count in each CPC class-year pair. We aggregate this measure to the firm-year level by computing the average number of normalized citations received by the patents that each firm applies for in a given year.

3.2.3 Market for technology

To examine how the relationship between firm size and invention quality changes when firms are able to sell their inventions, we construct a measure reflecting the level of activities in markets for invention using patent assignment data from the USPTO.[18] Using the USPTO's patent assignment dataset, we count the number of patents traded within each CPC class for a given year. We then derive the firm-year level measure by computing, for each firm and year, the average number of patents traded across the CPC classes weighted by the share of each firm's patents in those CPC classes.

3.2.4 Market for commercialization capabilities

We also explore whether the firms' ability to procure commercialization capabilities moderates the firm size relationship with average patent value and average quality. We construct for each 6-digit NAICS a measure of propensity to acquire new commercialization capabilities (i.e., share of firms within 6-digit NAICS that acquired new commercialization capabilities)

[18] https://www.uspto.gov/ip-policy/economic-research/research-datasets/patent-assignment-dataset

based on the division of innovative labor (DoIL) survey from Arora, Cohen and Walsh (2016). In particular, we use responses to question 9.2 of the survey, which asks respondents if they acquired new types of equipment or hired employees with skills different from existing employees to commercialize their most significant product innovation introduced in 2009, where "most significant" was that new product accounting for a plurality of sales revenue. While this measure should capture a component of the market for commercialization capabilities, it is not comprehensive in that the market for such capabilities extends beyond hiring or the purchase of equipment.

3.2.5 Diversification

We also explore whether invention quality should increase when the inventive activities of firms, controlling for size, are more diverse; that is, they span a larger number of technologies. To the degree that a firm's commercialization capabilities apply to different technologies and its inventive efforts are spread across more technologies, a firm's level of inventive effort in each technology will be less. As a consequence, given diminishing marginal returns, with less investment firms will tend to undertake projects with higher average quality. We construct a measure of technological diversification for each firm by counting the number of CPC classes in which a firm patents throughout the entire sample year, multiplied by one minus Herfindahl–Hirschman Index across the CPC classes to control for potential concentration of patenting activity within certain technology areas.

3.2.6 Descriptive statistics

Table 3 presents the summary statistics for the main variables used in our study. The observations are at the firm-year level. The average private value of the patents that a firm applies for in a given year is 13.5 million US dollars, with a standard deviation of 37 million US dollars. The average forward citations received by a patent, normalized by the mean citation count within each grant year and CPC class pair, is 1.3, with a standard deviation

Table 2: Variable Description

Variable	Measure	Description of measure
Average private value	Average patent value	Private value of patents to a firm is obtained from the data set constructed by Kogan et al. (2017) till 2010 and extended by Stoffman, Woeppel and Yavuz (Forthcoming) to 2015. These patent values are estimated by exploiting movements in stock prices following the days that patents are issued to the firm. The expected valuation of a patent is estimated by filtering the idiosyncratic stock return from normal stock market returns. This value is then divided by the number of patents that a firm was granted that day and multiplied by the market capitalization. The private value of a patent is averaged across granted patents applied for by a firm in a given year to compute the average patent value of a firm's patents.
	Share of multi-jurisdiction patents	This measure is defined as the share of inventions patented in multiple jurisdictions. We construct this measure by identifying patent families of a firm's patents for each year and finding the share of those families with patents in multiple jurisdictions.
Average quality	Average forward cites (Avg. Cites)	Patent quality is measured using forward citations. Forward citations to patents are obtained from PATSTAT. These are weighted by the average forward citation in the focal patent's three digit CPC and grant year cohort. These weighted forward citations of patents is averaged across patent applications of a firm in a given year to get the average quality of innovation to a firm from its granted patents.
Firm size	Sales	Firm size is measured using sales of the firm from Compustat. We use the lagged value of sales, lagged one year prior to the application year of the patent, as an empirical proxy for ex ante firm size.
Markets for Technology	MFT	We use reassignments to construct a measure of propensity to sell patents. Using the USPTO's patent assignment dataset, we count the number of patents traded within each CPC class for a given year. We then derive the firm-year level measure by computing, for each firm and year, the average number of patents traded across the CPC classes weighted by the share of each firm's patents in those CPC classes.
Markets for Commercialization Capabilities	MFC	The measure of commercialization capabilities is constructed using the average response to the question about using new types of equipment or hiring new employees to commercialize new or significantly improved goods and services in a six digit NAICS industry code.
Diversification	Diversification	The measure of diversification is constructed by multiplying the number of CPC classes that a firm patents by (1-HHI_{CPC3}), where HHI_{CPC3} is the Herfindahl–Hirschman Index across the CPC classes that the firm patents in. Using this measure, we construct an indicator variable taking the value 1 if the firm is above the median of the measure, and 0 otherwise.
	Stirling Index	This index is constructed by taking the sum over the product of share of patents in each CPC class pair and the distance between each CPC pair of a firm. The distance between each CPC class pair is calculated as a range between 0 and 2, where 2 is the distance between two completely distinct CPC classes, 1 is the distance between CPC classes whose CPC section is the same and 0 is for firms that patent only in one CPC class. The final measure is log-transformed.
Centered US Tariffs	(Centered) Tariffs	This variable is constructed using a simple average of tariffs charged by US on its imports from the rest of the world. Average tariffs are demeaned across years for each four digit SIC and weighted by the firm's share of sales in each SIC using primary SIC codes from compustat historical segment files.

of 1.6. Consistent with findings from prior studies (Kogan et al., 2017; Gambardella, Harhoff and Verspagen, 2008), the distribution of value and quality of patents is right-skewed.[19]

Table 3: Summary Statistics for Main Variables

	Obs	Mean	SD	10%	50%	90%
Avg. quality	26,468	1.32	1.60	0.31	0.99	2.45
Avg. value (mil. USD)	26,468	13.5	37.2	0.46	3.82	28.6
Diversification	26,468	3.25	6.13	0	1	8.54
Employees ('000's)	26,252	11.4	34.0	0.09	1.55	29.2
Market capitalization (mil. USD)	26,430	4,173	19,182	30.5	364	6,694
MFC	19,166	0.60	0.18	0.43	0.60	0.80
MFT	26,468	357	659	11.3	158	760
Patent stock	26,468	157	572	2	17.5	322
Publication stock	26,468	101	465	0	4.87	128
Sales (mil. USD)	26,462	3,086	13,750	8.23	263	5,673
Share of multi-juris. patents	26,468	4.06	3.51	1	3	8.05
US Tariffs (centered)	18,697	0.05	1.17	-0.99	-0.10	1.41

Notes: This table provides a summary of the main variables used in our study. The sample is restricted to 2,786 U.S. headquartered publicly traded firms in the DISCERN dataset for the period 1980-2015. The sample is further restricted to manufacturing firms (SIC 2000-3999). *MFT* is the number of patents reassigned within each CPC class, weighted by the share of the firm's patents in each CPC class. *MFC* is based on the division of innovative labor (DoIL) survey (Cohen, Lee and Walsh, 2021), and is the share of firms within each 6-digit NAICS that acquired new equipment or hired new employees to commercialize inventions. *Diversification* is a continuous variable constructed by multiplying the number of CPC classes that a firm patents in for a given year by (1-HHI_{CPC3}), where HHI_{CPC3} is the Herfindahl–Hirschman Index across the CPC classes that the firm patents in for a given year. The measure *Centered US tariffs* is constructed using a simple average of tariffs charged by US on its imports from the rest of the world. This measure is demeaned across years for each four digit SIC and weighted by the share of sales each firm in an SIC. We use Centered US tariffs to instrument for firm sales.

Average sales and market capitalization for our sample firms are 3.1 billion US dollars with a median of 263 million US dollars and 4.2 billion US dollars with a median of 364 million US dollars, respectively. The high averages are driven by a few large firms at the top of the distributions. To account for the highly skewed distributions, we log transform these variables in our analyses.

[19] At the patent level, the average value of a patent is 22.3 million US dollars, and the median value of a patent is 6.8 million US dollars. The average patent in our sample receives 1.1 forward citations at the mean, and 0.5 at the median.

3.3 Non-parametric results

To understand how average private value and quality of a firm's invention vary with size, in Figure 2, we plot firm size against private value of an invention (left vertical axis) and invention quality (right vertical axis). Patent values are from Kogan et al. (2017) and are averaged over the patents that each firm applies for in each year, and invention quality is proxied by the average number of forward citations received by the patents that each firm applies for in each year, where forward citations are normalized (i.e., divided by) by grant year-CPC class mean. Firm size quartiles are based on firm sales at the firm-year level.

The figure shows that average private value of patents (left vertical axis) represented by the solid line is systematically higher for larger firms. More specifically, moving from the bottom to the top firm size quartile, the average private value of patents rises around ten fold, that is, from around 3.6 million US dollars to 35 million US dollars. At the same time, consistent with superior appropriability being the principal source of the size premium, average patent quality (right vertical axis) represented by the dotted line declines with firm size. Moving from the bottom to the top quartile of firm size distribution is associated with about a 26% decline (i.e., from 1.54 to 1.15) in the average number of citations.

3.4 Econometric results

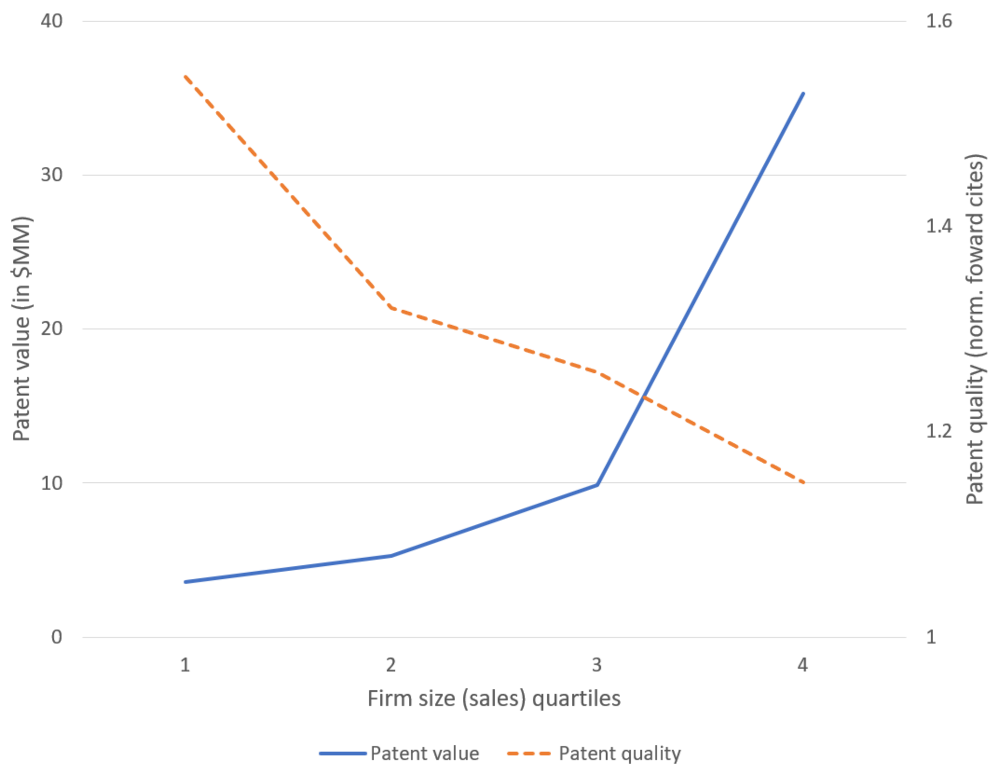
3.4.1 Private value of invention

We use the following econometric specification to test the relationship between firm size and invention value:

$$ln(\chi_{it}) = \alpha_0 + \alpha_1 ln(Sales_{it-1}) + \phi_i + \tau + \varepsilon_{it} \tag{1}$$

The dependent variable χ_{it} is the average private value of the patents that firm i applies for in year t. $Sales_{it-1}$ is sales of firm i in year $t-1$. Both the dependent and independent variables are in log terms. Therefore, the coefficient α_1 is the elasticity of average private value of an invention with respect to sales. ϕ_i and τ are complete sets of firm and year

Figure 2: Firm size, patent value, and patent quality



Notes: The figure presents the relationship between firm size and patent value as well as between firm size and patent quality. The sample consists of Compustat firms between 1980 and 2015. Patent value is from (Kogan et al., 2017) and is the mean value of patents produced by each firm for each year. Patent quality is the number of forward citations received per patent produced by each firm for each year. Patent citation is normalized by CPC class-year mean.

dummies. ε_{it} is an iid error term. Standard errors are clustered at the firm level. The coefficient of interest is α_1. We expect $\alpha_1 > 0$ if large firms realize higher value from their inventions.

Table 4 presents estimation results for equation 1. Columns 1 and 2 report between- and within-firm estimates, respectively. Both indicate a sizable positive association between the average patent value and size. Column 2 shows that firm size and private value of an invention has a statistically significant and positive relationship, and indicates that, a doubling of firm size is associated with approximately 16% increase in private value of an invention. Comparing columns 1 and 2 shows that the inclusion of firm fixed effects reduces the coefficient estimate of firm sales by about 60%, suggesting substantial heterogeneity across firms in the relationship between size and value. In most of our analyses, we will feature the within-firm effects, thus focusing on the question of whether firms are able to realize higher value from their inventions as they grow.

Column 3 reports within-firm estimates after controlling for differences in patent and publication stocks. We include patent and publication stocks as controls for comparability with other studies of the research activities of firms (e.g., Hall, Jaffe and Trajtenberg (2005); Arora, Belenzon and Sheer (2021)).[20] The coefficients on patent and publication stocks indicate a negative relationship between average value and patent stock and a positive relationship between average value and publication stock. Column 4 further adds a control for market capitalization to reflect the fact that Kogan et al. (2017) estimate invention values based on movements in the share value and, in turn, the market value for each firm (Brav et al., 2018). As expected, the magnitude of the coefficient on firm sales declines substantially (by about 80%) after adding market capitalization. The results indicate that a doubling of firm size is associated with approximately 5% increase in the private value of an invention. [21] In column 5, as an alternative measure of average invention value, we use the share of a firm's inventions patented in multiple jurisdictions. The results indicate that a doubling of firm size is associated with 1.7 percentage point increase in the share of inventions patented in multiple jurisdictions.

The pattern of results presented in this section is consistent with the private value of inventions increasing with firm size. Note, however, that market capitalization is strongly correlated with sales (r = 0.72). As a forward looking measure, it may also be correlated with unobserved variation in the value-capture capabilities of the firm.

[20] These stocks reflect the scale of the firm's inventive effort, which itself reflects both its inventive ability and its ability to capture value from inventions.

[21] At the sample mean, a doubling of firm size is associated with approximately 0.8 million US dollars. At the median, a doubling of firm size is associated with an increase in private value of 0.7 million US dollars.

Table 4: Relationship between Firm Size and Private Value of Inventions

Dependent variable	ln(Average patent value)				Share of multi-juris. patents)
	(1)	(2)	(3)	(4)	(5)
VARIABLES	Btw-Firm	Within-Firm	Stock	Market Cap	Jurisdictions
$\log(1+\text{Sales})_{t-1}$	0.405	0.161	0.224	0.053	0.017
	(0.010)	(0.019)	(0.021)	(0.018)	(0.005)
$\log(1+\text{Patent stock})_{t-1}$			-0.147	-0.138	
			(0.019)	(0.018)	
$\log(1+\text{Publication stock})_{t-1}$			0.002	-0.002	
			(0.021)	(0.018)	
$\log(1+\text{Market capitalization})_{t-1}$				0.284	
				(0.012)	
Firm dummies	No	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes
SE Clustered	Firm	Firm	Firm	Firm	Firm
Mean of DV	13.48	13.62	14.08	14.08	0.83
Observations	26,468	26,152	24,572	24,529	26,152
R-squared	0.50	0.87	0.88	0.89	0.38

Notes: This table presents the relationship between average private value of inventions and firm size. The sample consists of 2,786 public firms (from Compustat) and covers years 1980 through 2015. Average private value is from Kogan et al. (2017) and is based on abnormal stock market returns returns in response to patent issuance. Firm sales is lagged by one year. Publication stock and Patent stock are from Arora, Belenzon and Sheer (2021). Clustered standard errors are reported in parentheses.

3.4.2 Invention quality

Given that as firms grow larger, they are able to realize higher value from their inventions, we now explore whether that is due to an advantage in inventive capability or an advantage in their ability to capture value. Recall that our model predicts that, if the size premium is due to greater inventive capability, the relationship between quality and size should be positive. However, if the size premium is due to higher value-capture, the relationship should be negative. We use the following econometric specification:

$$ln(Quality_{it}) = \beta_0 + \beta_1 ln(Sales_{it-1}) + \phi_i + \tau + \varepsilon_{it} \tag{2}$$

The dependent variable $Quality_{it}$ is the average quality of the patents that firm i applies for in year t. The coefficient of interest is β_1 as we are interested in examining how invention quality varies with firm size. We expect β_1>0 if large firms are able to realize higher value from their inventions due to advantages in inventive capability (model prediction 1) and

$\beta_1 < 0$ if large firms are able to realize higher value from their inventions due to advantages in value-capture (model prediction 2).

Table 5 presents estimation results for equation 2. Columns 1 and 2 report between- and within-firm estimates, respectively. They indicate that firm size and invention quality has a negative and statistically significant relationship. The column 2 estimates indicate that when firm size doubles, the invention quality declines by approximately 3.4%. Comparing columns 1 and 2, we see that the inclusion of firm fixed effects increases the coefficient estimate over tenfold in magnitude and renders the coefficient statistically significant. This change in coefficient estimates and significance suggests that there is significant unobserved heterogeneity across firms in the average quality of inventions. Sources of unobserved heterogeneity may include persistent differences in firms' inventive capabilities, reflected in invention quality differences between firms, that are positively associated with size, as well as differences in the technology classes in which they patent.

Column 3 reports within-firm estimates after controlling for differences in patent and publication stock, and column 4 adds a control for market capitalization to facilitate comparison with the estimates for value. Patent stocks and publication stocks are highly correlated with size, leading to noisy coefficient estimates. The results in column 4 show that doubling of firm size is associated with around 2.7% decline in invention quality, or 0.04 fewer (normalized) citations at the sample mean.[22]

In column 5, we use inverse hyperbolic sine transformation for average forward citations to account for the fact that some patents receive no citations. The results continue to show a statistically significant and negative coefficient on sales, indicating that invention quality has a negative relationship with firm size.

Taken together, the results from Tables 4 and 5 indicate that increases in firm size are associated with an increase in average patent value and a modest lowering of average patent

[22] In unreported analysis, we regress average quality on firm sales for the post-2000 sample period after excluding examiner added citations and find qualitatively similar and statistically significant results. Examiner citations are identifiable only since 2000.

quality. The general pattern of results from our analysis on the relationship between firm size and invention quality is consistent with large firms realizing higher value from their inventions due to their advantages in value-capture.

Table 5: Relationship between Firm Size and Invention Quality

Dependent variable	ln(1+Average forward cites)				asinh(Avg. forw. cites)
	(1)	(2)	(3)	(4)	(5)
VARIABLES	Btw-Firm	Within-Firm	Stock	Market Cap	IHS
log(1+Sales)$_{t-1}$	-0.003	-0.034	-0.023	-0.027	-0.035
	(0.002)	(0.006)	(0.006)	(0.007)	(0.009)
log(1+Patent stock)$_{t-1}$			-0.015	-0.015	-0.021
			(0.006)	(0.006)	(0.009)
log(1+Publication stock)$_{t-1}$			-0.013	-0.013	-0.017
			(0.007)	(0.007)	(0.010)
log(1+Market capitalization)$_{t-1}$				0.007	0.009
				(0.005)	(0.007)
Firm dummies	No	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes
SE Clustered	Firm	Firm	Firm	Firm	Firm
Mean of DV	1.32	1.32	1.30	1.30	1.30
Observations	26,468	26,152	24,572	24,529	24,529
R-squared	0.01	0.44	0.43	0.44	0.43

Notes: This table presents the relationship between invention quality (average forward citations) and firm size (firm sales) at the firm-year level. The sample consists of 2,786 public firms (from Compustat) and covers years 1980 through 2015. Forward citations are weighted by the average value in their cohort (CPC class and grant year). Firm sales is lagged by one year. Publication stock and Patent stock are obtained from Arora, Belenzon and Sheer (2021). Clustered standard errors are reported in parentheses.

4 Commercialization capabilities and the appropriability advantage

Having established in the prior section that large firms benefit from an appropriability advantage in invention, this section considers the source of that advantage, specifically the role of commercialization capabilities. Lacking a measure of commercialization capabilities, we make the case indirectly. We identify the circumstances under which firms' prior possession of commercialization capabilities confers less of an advantage, which, in our model, should moderate the links between firm size and, respectively, the value and quality of inventions.

We then test these predictions.

4.1 Model

If we relax the assumption that firms must embody their inventions in their own output by assuming that firms can sell or license their inventions, the relationship between average private value and firm size should weaken. A market for technology offers a firm the option to buy or sell. A firm with strong commercialization capability–a large firm–may continue to commercialize internally. It would reduce internal R&D so as not to invent incremental inventions and instead acquire inventions from the outside and deploy its commercialization capabilities to those inventions. Firms lacking commercialization capability–small firms–would, instead, increase R&D (Arora and Ceccagnoli, 2006) to sell additional inventions to other, larger firms with superior commercialization capabilities, realizing gains from trade. The quality of inventions of large and small firms would become more similar, as would the private value of inventions.[23]

This argument can be illustrated with a simple example. Suppose firm i can license its inventions with probability λ to a potential licensee with a value for the invention of quality q given by $\bar{v}q, \quad \bar{v} > v$. Suppose firm i can capture a fraction $\gamma, 0 < \gamma \leq 1$ of the total value generated, such that, the licensing fees are equal to $(v + \gamma(\bar{v} - v))q$. Thus its expected payoff (gross of costs) is $\tilde{v}q$, where $\tilde{v} = v + \lambda\gamma(\bar{v} - v) > v$. Thus, when the inventor can license, this is equivalent to the inventor being able to capture value that a larger firm could capture. Note that for firms with high appropriability due to superior commercialization capabilities, $v > \bar{v}$, their value-capture is not increased by the option of licensing, and thus licensing is not attractive to them. This implies that average value of inventions is less dependent on size when firms can license. As a consequence, quality will also depend less on size since expected value drives the projects that firms pursue. This result also highlights

[23] Furthermore, firms might specialize. A firm might invest in R&D and other assets that would increase the quality and quantity of inventions, or it might invest in production, and sales and marketing, and other capabilities that enable it to efficiently commercialize inventions.

the importance of commercialization capabilities as the means for value-capture since the reason that smaller firms benefit from licensing is that licensing provides indirect access to the superior commercialization capabilities of potential licensees.

When the size premium is due to superior appropriability, the option to sell or license their inventions will dampen the differences between large and small firms in terms of both quality and value. If instead the size premium is due to superior inventive capability, A, average quality increases with size. However, the option to license would encourage larger firms with weak commercialization but high inventive capabilities to invent more, and move down the marginal product curve. As a result, average quality would increase with size more slowly than if licensing were not possible.[24]

If commercialization capabilities could be rented or otherwise acquired by the inventor, the outcome is similar to that when firms can license their inventions. Assuming no capital constraints, the value of invention would not depend on the existing commercialization capabilities of a firm. To the extent that markets for commercialization capabilities are pervasive within an industry, we expect the firm size relationship with both invention value and quality to weaken if size is associated with superior commercialization capability. On the other hand, if size is associated with superior inventive capability, the relationship between size and average value would be strengthened.

A market for technology also allows for in-licensing. Suppose a firm can in-license inventions with an average quality of $\underline{q}$. It follows that it will not develop internal inventions with quality lower than $\underline{q}$. If size is associated with greater appropriability, the option to in-license will imply that the average quality of internal inventions will fall more slowly with size. But the same logic implies that average value would increase at a higher rate with appropriability. Recall that as appropriability, v, increases, the effect on average value is partially reduced by a reduction in average quality. If average quality diminishes at a lower rate because of the floor provided by outside inventions, average value will increase at a

[24]See appendix A.3 for a formal proof.

higher rate with superior appropriability due to size.

If the size premium is due to superior inventive capability, average quality increases with size. In an MFT, smaller firms are more likely to in-license, thereby reducing the positive relationship between average quality and size, as well as reducing the positive relationship between average value and size.[25]

To summarize, when companies have the option of licensing inventions from others, or license their inventions to others, or acquire commercialization capabilities from outside, the relationship between average quality and size will weaken. This is the case whether size is associated with greater appropriability or with superior inventive capability.

However, the relationship between average value and size depends on whether the firm is principally licensing its inventions to others or mainly licensing inventions from the outside. The relationship will be weaker when size is associated with greater appropriability and the firm licenses to others, and when size is associated with superior inventive capability and firms can in-license. The relationship will be strengthened if size is associated with superior inventive capability and firms license their inventions to others. The relationship will also be strengthened if size is associated with greater appropriability and firms in-license inventions from the outside.[26]

Empirically, this implies that if the size premium is due to inventive capability, the interaction between MFT and size should be negative for quality. If the size premium is due to appropriability, the interaction between MFT and size should be positive for quality. These are summarized in rows 1 and 2 of Table 6. Rows 3 and 4 indicate the relationship between average value and size.

[25] See appendix A.4 for a formal proof.

[26] In our sample, as explained in detail in footnote 28 below, firms tend to out-license more. Thus, we should expect the interaction between MFT and size in the value equation to be positive if size premium is from ability and negative if the premium is due to appropriability.

Table 6: Empirical predictions under markets for technology (comparing the out-licensing and in-licensing cases) and under markets for commercialization capabilities (MFC)

		Out-licensing		In-licensing		MFC	
		Inventive Capability (A) (1)	Appropri-ability (v) (2)	Inventive Capability (A) (3)	Appropri-ability (v) (4)	Inventive Capability (A) (5)	Appropri-ability (v) (6)
Average Quality	**Size**	Positive	Negative	Positive	Negative	Positive	Negative
	Size*Markets	Negative	Positive	Negative	Positive	Negative	Positive
Average Value	**Size**	Positive	Positive	Positive	Positive	Positive	Positive
	Size*Markets	Positive	Negative	Negative	Positive	Positive	Negative

Notes: This table summarizes the results from comparative statics of average private value and average quality with respect to inventive capability and appropriability, under out- and in-licensing of inventions, and when there are a market for commercialization capabilities (MFC). Note that the empirical predictions from the model are similar in the cases of out-licensing and MFC.

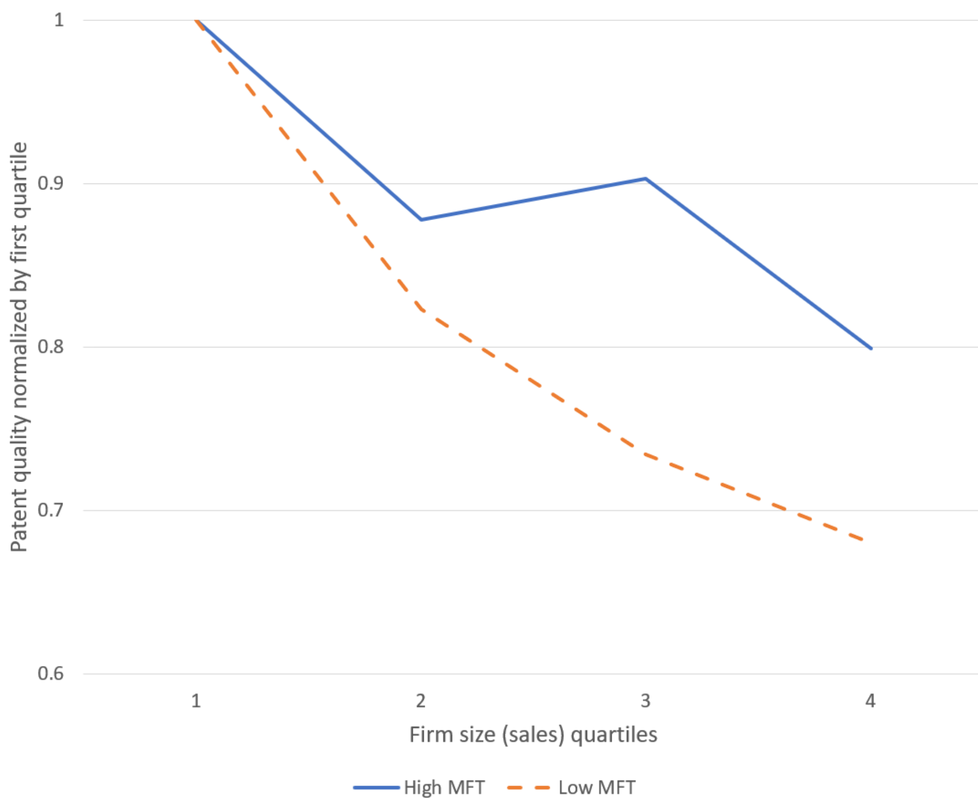
4.2 Non-parametric results

Figure 3 presents the relationship between firm size and invention quality (normalized by the first size quartile) for firms that are more likely to trade their inventions (upper half of trade propensity distribution) and for firms that are less likely to trade their inventions (lower half of trade propensity distribution).

The figure shows that the relationship between firm size and invention quality is weaker for firms that are more likely to trade their inventions. Specifically, for firms in the upper half in terms of propensity to trade patents, moving from the bottom to the top quartile of firm size distribution, the average quality of inventions drops by around 20%. The average quality drops by 32% for firms in the lower half of trade propensity distribution.

Figure 4 shows that the relationship between firm size and invention quality (normalized by the first size quartile) is weaker for firms better able to acquire new commercialization capabilities. Specifically, for firms operating in industries in the top quartile of the propensity to acquire new commercialization capabilities, moving from the bottom to the top quartile of firm size distribution is associated with around 4% drop in the average quality of inventions. The average quality drops by 28% for firms in the lower three quartiles of the distribution.

Figure 3: Firm size, patent quality, markets for technology



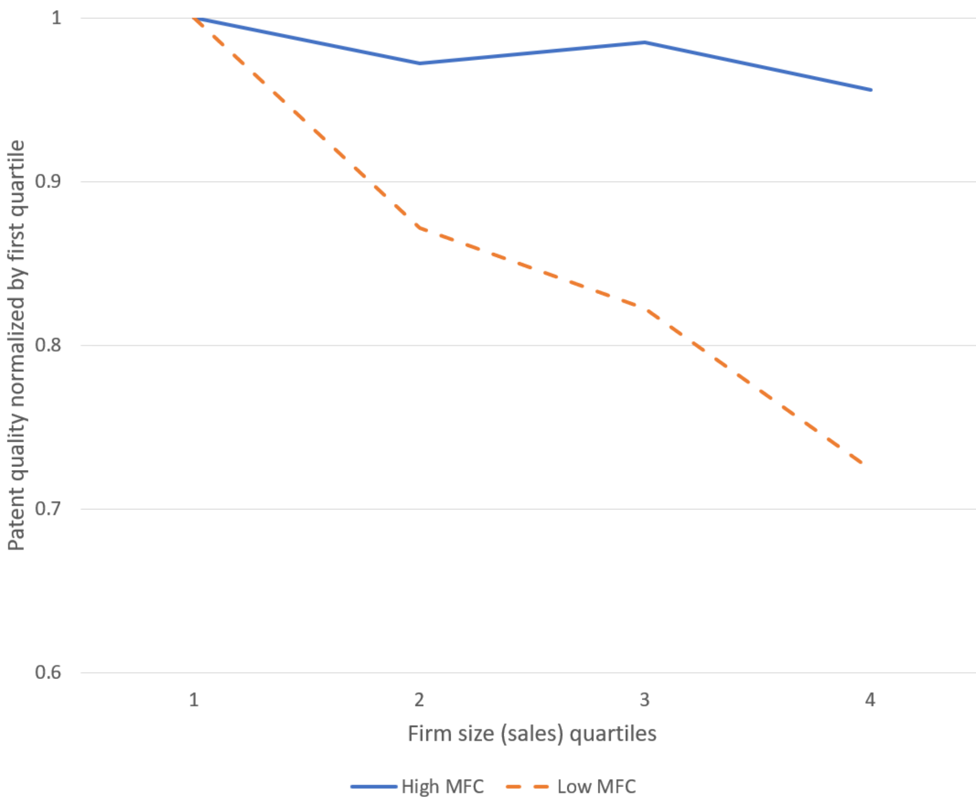
Notes: The figure presents the relationship between firm size and patent quality for firms in the top half of reassigned patents versus firms in the bottom half. The measure of reassignments is the number of patents reassigned in each 3-digit CPC for each sample year and aggregated to the firm-year level by taking the weighted average based on a firm's patenting propensity in a 3-digit CPC. Patent quality is normalized by the average quality of patents in the first quartile of sales distribution.

4.3 Econometric results

Table 7 presents our results characterizing the relationship between firm size and, respectively, private value and invention quality when either markets for technology (MFT) or markets for commercialization capabilities (MFC) are pervasive.

In Table 7 we once again observe a positive relationship between size and value and a negative relationship between size and quality. More importantly, in columns 1 and 4, the coefficient estimates for the interactions of sales with MFT show a weakening of firm size

Figure 4: Firm size, patent quality, and markets for commercialization capability



Notes: The figure presents the relationship between firm size and patent quality for firms in industries in the top quartile of MFC distribution, and 0 otherwise. MFC is an industry-level measure of propensity to acquire new commercialization capabilities (i.e., share of firms within 6-digit NAICS that acquired new commercialization capabilities) based on Cohen, Lee and Walsh (2021). Patent quality is normalized by the average quality of patents in the first quartile of sales distribution.

relationship with private value and invention quality as MFT increases.[27] This is consistent with our model prediction (see Table 6) for the case where larger firms benefit from an appropriability advantage and: 1) markets for technology are more pervasive; and 2) firms are predominantly using such markets to sell their inventions (e.g., via out-licensing, or selling their patent rights via reassignments). The negative and statistically significant coefficient on the interaction term in column 1 shows that the relationship between firm size and private value of an invention is about 13% weaker (interaction coefficient is statistically significant

[27]In columns 1 and 4, firm sales is interacted with a continuous measure indicating the level of activity in markets for technology.

at the 5% level) for firms operating industries with more active markets for inventions. Also, column 4 shows a positive and statistically significant coefficient on the interaction term, indicating that the relationship between firm size and invention quality is about 11% (statistically significant at the 5% level) weaker for firms operating in industries with more active markets for inventions.[28] This weakening of the firm size relationship with both quality and value suggests that where firms do not need to possess commercialization capabilities themselves, but can sell their inventions via MFT to earn higher returns, the size advantage diminishes.

We next explore the moderating effect on size of markets for commercialization capabilities (MFC). Paralleling our argument regarding MFT, to the extent that firms operate in industries where commercialization capabilities are more readily procured, we again expect a weaker relationship between firm size and invention quality and value to weaken. Columns 2 and 5 of Table 7 report our estimation results. In both columns, firm sales is interacted with a continuous measure of MFC, defined as the share of firms that have either acquired new equipment or hired new employees to commercialize their most significant innovation in a 6-digit NAICS.

Consistent with the expectation, the coefficient on the interaction term for the value regression in column 2 is negative. Although the coefficient is not statistically significant, the magnitude is quite large, about 88% of the coefficient on sales. Also, consistent with the expectation, the coefficient on the interaction term for the quality regression in column 5 is positive and statistically significant at the 5% level. The magnitude of the coefficient is again quite large at 99% of the coefficient on sales. These results suggest that the firm size relationship with value and quality may be substantially diminished when firms can acquire the capabilities required to commercialize their inventions.

[28]It should be noted, however, that our model predicts a strengthening of the relationship between size and private value where firms acquire inventions via MFT's. In our sample, firms typically sell rather than buy inventions. Approximately 58% of the firms in our sample have reassigned their patents at least once, and 46% have acquired patents. Of the 71% of firms have sold or bought patents in our sample, 35% have only sold patents, compared to 18% that have only bought patents. The remaining 47% have both sold and bought patents.

To summarize, it appears that it is the prior possession of commercialization capabilities of larger firms that allow them to extract more value from their inventions. We demonstrate this argument through exception–by showing that where the prior possession of commercialization capabilities is not essential for firms to profit from their inventions, the link between firm size and, respectively, invention quality and private value weakens.[29]

Lastly, we explore the relationship between firm technological diversification and average invention value and quality, while controlling for firm size. To the extent that the firm's commercialization capabilities are specific to technology areas, we expect that more diversified firms on average will realize lower value from their inventions and generate higher quality inventions than focused firms.

Consistent with the expectation, the results in column 3 show that diversification has a negative relationship with average private value of inventions, indicating that doubling the level of diversification is associated with about 3% decline in average private value of inventions. Column 6 shows that diversification has a positive relationship with average invention quality, indicating that doubling the level of diversification is associated with about 4% increase in average invention quality.[30] What this suggests is that, through technological diversification, the value and quality of the inventions of a larger firm can begin to resemble the value and quality of a smaller firm's. This result also suggests that, to some degree, the commercialization capabilities of firms may be specific to the different areas of technical specialization within it. For example, one would not expect the marketing, sales, and manufacturing capabilities for the jet engine division of GE to be useful in commercializing innovations from GE's medical imaging division.

[29] A link between firm size and the ability to manage and enforce patents could also explain our findings of a positive relationship between firm size and value and a negative one between firm size and quality. Under some assumptions, that counterargument could also explain the weakening of the observed relationships when markets for technology are strong. However, this counter-argument is not consistent with the weaker relationships estimated when markets for commercialization capabilities are strong.

[30] In Appendix Table C.8, we use an alternate measure of diversification based on Stirling (2007) and find qualitatively similar results for both the value and quality regressions.

Table 7: Markets for Technology and Capabilities and Firm Diversification

Dependent variable	ln(Avg. private value)			log(1+Avg. forward cites)		
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	MFT	MFC	Diversif.	MFT	MFC	Diversif.
log(1+Sales)$_{t-1}$	0.146	0.090	0.055	-0.063	-0.070	-0.030
	(0.026)	(0.050)	(0.018)	(0.010)	(0.022)	(0.007)
log(1+Sales)$_{t-1}$ x MFT	-0.019			0.007		
	(0.004)			(0.002)		
log(1+Sales)$_{t-1}$ x MFC		-0.076			0.069	
		(0.083)			(0.035)	
Diversification			-0.029			0.039
			(0.014)			(0.006)
MFT	0.078			-0.052		
	(0.022)			(0.010)		
log(1+Patent stock)$_{t-1}$	-0.127	-0.131	-0.135	-0.016	-0.014	-0.019
	(0.017)	(0.020)	(0.017)	(0.006)	(0.008)	(0.006)
log(1+Publication stock)$_{t-1}$	0.004	0.021	-0.003	-0.015	-0.010	-0.012
	(0.018)	(0.021)	(0.018)	(0.007)	(0.009)	(0.007)
log(1+Market Capitalization)$_{t-1}$	0.288	0.270	0.287	0.005	0.008	0.003
	(0.012)	(0.014)	(0.012)	(0.005)	(0.006)	(0.005)
Firm dummies	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
SE Clustered	Firm	Firm	Firm	Firm	Firm	Firm
Mean of DV	14.08	13.87	14.08	1.30	1.32	1.30
Observations	24,529	17,634	24,529	24,529	17,634	24,529
R-squared	0.89	0.88	0.89	0.44	0.45	0.44

Notes: This table presents the firm size relationship with invention value and quality moderated by active markets for technology and commercialization capabilities (Columns 1-2 and 4-5). It also presents the relationship between firm diversification and invention value and quality (Columns 3 and 6). *MFT* is the number of patents reassigned within each CPC class, weighted by the share of the firm's patents in each CPC class. *MFC* is the share of firms within each 6-digit NAICS that acquired new equipment or hired new employees to commercialize inventions. *Diversification* is a continuous variable constructed by multiplying the number of CPC classes that a firm patents in for a given year by (1-HHI_{CPC3}), where HHI_{CPC3} is the Herfindahl–Hirschman Index across the CPC classes that the firm patents in for a given year. Clustered standard errors are reported in parentheses.

5 Firm size and inventive capability: Non-parametric results

The model in section 3.1 is driven by the simple insight that a firm that can capture more value from its inventions will develop more inventions. Diminishing returns in invention quality imply that additional inventions will tend to be of lower quality, thereby reducing the *average* quality of inventions. It is possible, therefore, that a greater inventive capability may be masked by the effect of diminishing returns. If one assesses not the quality of the average invention but instead the quality of the "best" (i.e., highest quality) inventions, the effect of diminishing returns will be muted. That is, in terms of the model, instead of testing whether $\frac{Q(n;A)}{n}$ increases with size, we could test whether $Q(0;A)$ increases with size.

Doing so raises, however, a different problem. Even if $Q(0;A)$ did not increase with size, if we measure $Q(0;A)$ with noise, an increase in the number of patents a firm files will bias the estimate of $Q(0;A)$ upwards. A simple example illustrates the point. Consider two firms with the same total quality function, $Q(n)$. Assume firm a, being larger, has a higher v than firm b, and therefore produces more patents i.e., $n_a > n_b$. Quality is measured with error, so the quality of the i^{th} patent is $Q(i) + \epsilon_i$. The expected quality of "best" patent of firm $k, k = \{a, b\}$ has quality given by $\mathbb{E} \max_{i=0}^{i=n_k} \{Q(i) + \epsilon_i\}$, which increases with n_k. As a result, firm a will have a higher quality "best" patent compared to firm b, though they have identical inventive capability (they have the same $Q(n)$). This implies that we have to control for the number of patents filed. However, simply including a linear control, as in a regression, is insufficient because of the expected value of an order statistic from a sample is inherently non-linear in the sample size. We therefore use a non-parametric approach to test whether large firms have superior inventive capabilities.

In Figure 5, we compare the citations received by the highest quality patents while controlling for differences in the number of inventions that firms generate in a given patent class (i.e., CPC class). The X-axis is firm sales quartiles, and the Y-axis is the average number of citations that the highest quality patents receive in a given firm size quartile, CPC class, and year. The square markers represent highest quality patents, and the round markers represent the average of the top three highest quality patents. Because large firms overall tend to produce many more patented inventions than small firms, we compare the quality of inventions only for firms producing a similar number of patents in a given CPC class over our sample period. Intuitively, we are comparing the best patents of large and small firms, as measured by sales, where we compare a group of large firms with a group of small firms such that both groups have the same number of patents in a CPC. Specifically, within each CPC class, we identify firms that generate 1-5, 6-10, 11-15, and so on, up to 201-205 inventions ("count groups").[31] Then, we find the highest quality patent within each sales quartile for a given CPC class-count group pair. Lastly, for each sales quartile, we average the citations that the highest quality patents receive across all count groups and CPC classes.[32]

The figure shows no apparent evidence of large firms having an advantage in inventive capability as the number of citations received by the highest quality patents (square markers) is similar between firms in the bottom and the top quartiles of size distribution. The number of citations received by the highest quality patents of the firms in the bottom quartile of size distribution is 7.3, while that of the firms in the top quartile is 6.1. The comparison of the three highest quality patents (round marker) across firm size quartiles also shows no apparent evidence that large firms possess an advantage in inventive capability.

Appendix Figure C.1 presents a comparison of the highest quality inventions between small and large firms within each technology area (i.e., CPC section). The overall pattern continues to show no apparent evidence of large firms holding an advantage in inventive capability.

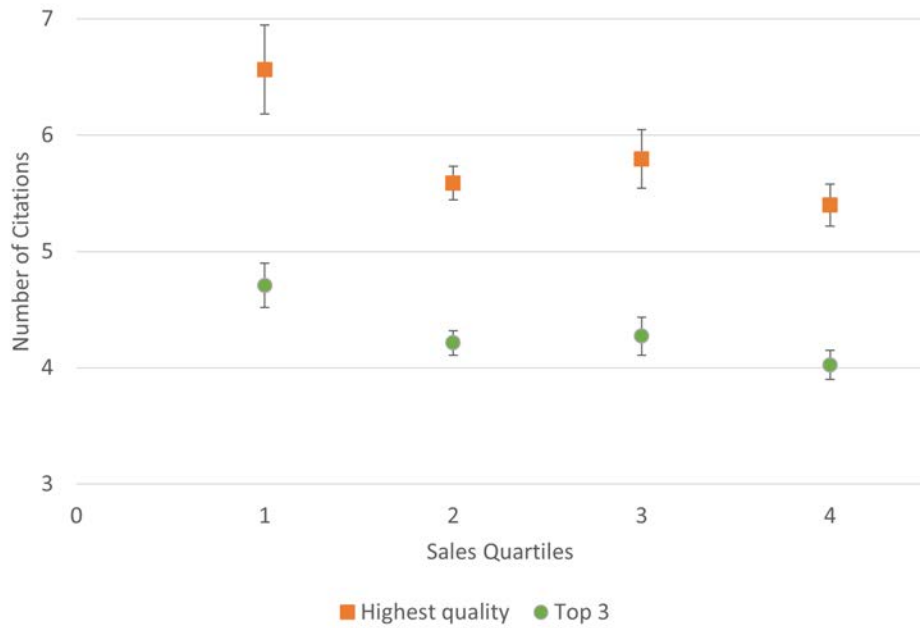
In Appendix Figure C.2, we compare the CDF of citations received by the top 1% cited patents of small and large firms while controlling for differences in the number of inventions that firms of different sizes generate. Appendix Figure C.3 shows the CDF of citations of top 1% cited patents, by technology area. We find the qualitatively similar result that large firms show no apparent evidence of holding an advantage in inventive capability.[33]

[31] We stop with the count group 201-205 to have a sufficient number of firms in our analysis. We set the threshold for the number of unique firms to be included in the analysis to 10.

[32] For example, if the highest quality patent in the bottom sales quartile of the firms generating 1-5 patents in a specific CPC class receives 15 citations and the highest quality patent in the bottom sales quartile of the firms generating 6-10 patents in the same CPC class receives 11 citations, then the average citations received by the highest quality patents generated by firms in the bottom sales quartile in that particular CPC class would be 13. This within-quartile average is computed for every CPC class, and the overall average for each quartile is computed from those averages.

[33] Appendix Table C.3 reports additional statistics and analysis to support figures C.2 and C.3. The first row of Table C.3, shows evidence that the mean of top 1% cited patents for large firms is lower for smaller

Figure 5: The quality of the top cited patents by sales quartiles



Notes: The figure presents the mean of the highest quality patents across all CPC classes by firm size (i.e., sales quartiles). The Y-axis is the number of forward citations that highest quality patents receive in a given firm size bin, CPC class, and year. Specifically, within each CPC class, we identify firms that generate 1-5, 6-10, 11-15, and so on, up to 201-205 inventions ("count groups"). We stop with the count group 201-205 to have a sufficient number of firms in our analysis. We set the threshold for the number of unique firms to be included in the analysis to 10. Then, we find the highest quality patent within each sales quartile for a given CPC class-count group pair. Lastly, for each sales quartile, we average the citations that the highest quality patents receive across all count groups and CPC classes.

6 Robustness tests

This section provides both an instrumented version of our quality equation results as well as a robustness test at the technology area level and another using an alternative measure of firm size.

firms. A Kolmogorov-Smirnov test of equality of CDFs can be rejected in favor of the alternate hypothesis that the CDF of quality of small firms lies below that of the CDF of quality for large firms. This pattern is also apparent within technology areas (except textiles and paper, fixed construction and electricity).

6.1 An additional test of the model: Using tariffs as a source of variation in value of inventions

The analysis so far examined how invention quality varies with firm size. In the value-capture interpretation, firm size proxies for commercialization capabilities that enable the firm to realize higher value from its inventions. It is then possible that the annual variation in sales within a firm may reflect unobserved factors that are related to the quality of future patents. In our model, such variations may reflect shocks to technological opportunity (represented by A) or shocks to the value of inventions (which were normalized to unity in the model.) Shocks to technological opportunity would be positively correlated with average quality. However, shocks to the value of inventions would lead the firm to move further down the marginal product curve, resulting in lower average quality of inventions. Tariffs can affect sales through changes in input cost and changes in product market competition, and thereby affect the value of inventions. This provides an additional test of our model, namely that average quality of inventions is negatively related to the average value.

We therefore use sales predicted by tariffs as a proxy for such shocks to value. In terms of our model, the shocks to value should be negatively correlated with average quality.[34] Compared to the OLS estimation, we observe that the coefficient on predicted sales in the 2SLS estimation in Appendix Table C.4 is an order of magnitude greater. Because unobserved shocks to technological opportunity may increase both quality and sales, it is not surprising that, once we strip that effect out, the estimated relationship between size and average quality becomes more negative.[35]

[34]Using predicted sales in the value equation does not provide a test because, by definition, shocks to value will be positively correlated with the average value of patents.

[35]For the discussion on construction of the instrument and a discussion of the first stage analysis, see Appendix B.5

6.2 Technology area-level analysis

Appendix Table C.5 presents the estimation results on the relationship between firm size and private value of an invention at the firm-technology area level. Consistent with the main findings, the results show that firm size and patent value have a positive association even with the inclusion of technology area dummies. For instance, column 5, which includes complete sets of year, firm, and technology area dummies, shows that doubling of firm size is associated with approximately approximately 6% increase in patent value (statistically significant at the 5% level), or around 1.2 million US dollars at the sample mean.

Appendix Table C.6 presents the estimation results on the relationship between firm size and invention quality at the firm-technology area level. The general pattern of results is consistent with the main finding that firm size has a negative association with invention quality. For instance, column 5, which includes complete sets of year, firm, and technology area dummies, shows that doubling of firm size is associated with approximately 2% decline in invention quality (statistically significant at the 5% level), or around 0.03 fewer (normalized) citations at the sample mean.

6.3 Alternative measures of firm size

To mitigate the potential concern that firm sales do not adequately capture the level of assets and capabilities that firms possess, we present additional results using an alternative measure of firm size - i.e., the count of employee. Appendix Table C.7 presents the estimation results on the relationship between firm size proxied by employee count and both invention value (columns 1 and 2) and quality (columns 2 and 3). Consistent with our main findings, columns 1 and 2 show that firm size has a positive relationship with invention value. (Only column 2 using a dummy variable indicating a large firm is statistically significant.[36]) Columns 2 and 3 show that firm size has a negative relationship with invention quality. (Only column 1 using a continuous measure of employee count is statistically significant.)

[36] A large firm is defined as a firm in the top half of the employee count distribution.

6.4 Inventions in the core technology area

It is possible that a firm's invention would be of higher quality when it is related to the prior inventions of the firm. Also, the tendency to make improvements over prior inventions can differ between large and small firms. To control for this possible difference, we reproduce our results after restricting the inventions used in our sample to those in the technology area within which each firm patents most frequently. Consistent with our main findings, the results in Appendix Table C.9 show that firm size has a positive relationship with invention value (column 1) and a negative relationship with invention quality (column 2).

7 Conclusion

In this paper, we observe a strong positive relationship between a firm's size, as measured by their sales, and the private value of their patented inventions—a finding consistent with the prior literature. A key objective of this paper is to understand the source of this relationship. We posit two possibilities: that larger firms are better at inventing, or that larger firms are better able to capture value from the inventions in their possession. We developed a simple model that allows for both possibilities. While the model predicts that invention value should increase with size in either case, the model also offers predictions that discriminate between the two. If inventive capability increases with size, then average quality should also increase. If the ability to capture value accounts for the relationship, then average quality should decline as firms grow.

In our empirical analysis, we feature Kogan et al. (2017) estimates of the values of firms' patented inventions as our primary measure of value, and the share of inventions patented in multiple jurisdictions as a second measure. We use forward citations as our measure of technical quality. Using a sample of 2,786 public corporations, our regression results show that larger size is indeed tied to a higher average private value of inventions. More tellingly, however, we find that average quality declines with size, suggesting that the main source of the size advantage is the ability to capture value—not inventive capability. This latter result does not, however, entirely eliminate the possibility that inventive capability may increase with size; larger firms may have a higher quality curve but move further down the curve, resulting in a lower average quality. To examine this possibility, we focus on the highest-quality inventions of different sized firms. Because the realized quality of the "best" inventions is a random variable, which depends not just on the inventive capability of the firm but also the number of patents it files, we conduct a non-parametric analysis that accounts for the differences in the number patents filed. The results of this analysis suggest that there is no relationship between firm size and inventive capability.

After establishing that it is an appropriability advantage that accounts for larger firms' realization of greater value from their innovations, we argue that it is larger firms' greater commercialization capabilities that confer that advantage. We make the case by identifying circumstances under which the appropriability advantage, if due to firms' commercialization capabilities, should weaken. Specifically, the large firm advantage should weaken if there is an active market for technology that enables inventors to capitalize on the commercialization capabilities of other firms, or if the inventing firm itself has ready access to commercialization capabilities. We indeed find that firm size advantage is weaker in industries where firms have access to markets for technology, allowing smaller inventors to profit from the commercialization capabilities of other firms by selling their IP to them. Similarly, in industries where firms can readily procure commercialization capabilities, the size advantage appears to be weaker as well. These results highlight the role that commercialization capabilities play in tying firm size to the quality and private value of invention.

The role of large, especially dominant firms in the economy has been a fraught question for 80 years since Schumpeter first suggested that large, monopolistic firms were the locus of technological change and, in turn, economic growth (Schumpeter, 1942). How we think about their role turns partly on our judgments about how such firms become dominant and what they contribute to the economy. What we have examined in this paper is not whether firms grow large because they are more productive per Autor, Dorn, Katz, Patterson and Van Reenen (2020), but whether firms' inventive efforts are more productive when they are large. Our results indicate that increases in firm size do not enhance inventive capability. Our analysis, however, would be consistent with a claim that larger firms' superior commercialization capabilities contribute to their further growth.

Our core finding that size confers an advantage for capturing value, likely via firms' commercialization capabilities, raises policy challenges. A key policy objective should be to support an economy's inventive capabilities. Our results are consistent with the simple logic of profit maximization operating on the diminishing productivity of firms' inventive efforts: As growth in size enables firms to reap greater profits from their inventions, they will move down the marginal productivity schedule, generating lower quality inventions, privately valuable but of less social value. Supporting smaller innovation-intensive firms will benefit the economy because, by virtue of their limited size and limited commercialization capabilities, smaller firms will tend to focus their efforts on the highest quality inventions. Such support can take the form of ensuring that market entry remains unfettered—especially that large, established firms are not permitted to suppress entry and venture creation.

Our paper is subject to a number of limitations. First, our sample is limited to public manufacturing firms, which means that "small" firms in our sample are still relatively large. The question is whether our findings would generalize to a more representative sample. Although ongoing research suggests a wider firm size distribution may well strengthen our findings[37], extending our analysis to a more representative sample would be useful. Second, we lack a direct measure of firms' commercialization capabilities. As a consequence, we can only provide indirect evidence consistent with our argument that commercialization capabilities account for the appropriability advantage of large firms. The absence of a measure of commercialization capabilities does not, however, weaken our more general point that the key to the large firm advantage is their superior ability to capture value from their inventions.

[37] Ongoing research by Pei (2022) and Johnson, Lipsitz and Pei (2022) suggests that private firms' patents are typically of higher quality and less redundant that those of larger, public firms.

Third, we do not model the process by which firms become large, nor the way in which associated factors might affect the observed relationship between size and, respectively, invention value and quality. Instead, we derive theoretical predictions that discriminate between competing explanations of the size premium, and, while making no causal claims, we test those predictions using simple regressions and non-parametric analyses.

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