Stronger patent law increases the allocation of resources to external relative to internal R&D: Empirical evidence

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Abstract

How should a technology firm adjust resource allocation between external and internal R&D in response to stronger patent protection? External R&D provides the firm with another channel of earnings to mitigate diminishing returns to internal R&D, but yields the firm only a fraction of the additional profit generated. Theoretically, if the marginal return to external R&D diminishes more slowly than the marginal return to internal R&D, the firm should increase external R&D more than internal R&D. Exploiting regional differences in the strengthening of patent protection due to the U.S. Court of Appeals for the Federal Circuit (CAFC), we find that the CAFC was associated with 35 percent more external R&D vis-a-vis 20 percent more internal R&D. The difference was more pronounced in industries where patents were less effective in the appropriability of product inventions and among firms more specialized in technology.

Keywords: External R&D, Appropriability, Innovation, Technology, Patent law

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1 Introduction

The allocation of technological resources is an important strategic decision for innovating firms (Levinthal and Wu, 2010). Stronger legal protection of patents increases appropriability and the expected returns from innovation activities as well as inducing more R&D (Qian, 2007; Czarnitzki and Toole, 2011). Yet, in an open innovation framework (Cassiman and Valentini, 2016), technology firms may perform R&D to produce technology for internal ownership ("internal R&D") as well as R&D to produce technology for ownership by others ("external R&D"). Internal and external R&D jointly affect innovation outcomes (Cassiman and Veugelers, 2006; Arora et al., 2007). Hence, it is imperative that managers consider how to strategically allocate limited technological resources between internal and external R&D, and how to adjust to changes in the appropriability regime.

— Figure 1 —

Referring to Figure 1, it seems fairly obvious that stronger patent protection would increase the appropriability of returns to both internal and external R&D, and so, the tech firm would increase both activities (Cassiman and Veugelers, 2002; Hernan et al., 2003; Bhattacharya and Guriev, 2006). The more challenging, open question is whether to allocate relatively more resources to internal or external R&D.[1]

Here, we examine how patent protection affects the allocation of limited technological resources. We begin with a simple model of a technologically capable firm seeking to maximize profit from external and internal R&D. External R&D provides a new channel of earnings to mitigate the diminishing marginal return to internal R&D. However, the tech firm receives only a fraction of the additional profit generated by external R&D. Theoretically, if the marginal return to external R&D diminishes at a slower rate than the marginal return to internal R&D, stronger legal protection of patents should induce

[1]The opening of the knowledge boundaries of the firm to engage in external R&D is fraught with moral hazard and hold-up, exacerbated by information asymmetries and sunk costs. Here, we focus on ensuring appropriability through patents. Besides, external R&D can be governed by relational (Lee and Png, 1990; Ryall and Sampson, 2009) and contractual (Aghion and Tirole, 1994; Oxley, 1997; Lerner and Malmendier, 2010; Bhattacharya et al., 2015; Crama et al., 2017; Guo et al., 2017) mechanisms.

the tech firm to increase more external relative to internal R&D. The effect would be amplified among businesses that are more specialized in technology and attenuated in industries where patent protection is more effective in appropriability.

We then test these propositions empirically, exploiting major changes in U.S. patent law around 1982-1985. U.S. patent law being federal, disputes are tried in the relevant District Court. Originally, appeals were heard by the regional Circuit Courts of Appeals. Although supposedly administering the same federal law, the various circuits varied considerably in their decisions and even conflicted. In 1982, the U.S. Congress established the Court of Appeals for the Federal Circuit (CAFC) to unify appeals and harmonize the interpretation of the law. Over time, the CAFC shifted the law, mostly in favor of patent owners (Dreyfuss, 1989; Seamon, 2003; Atkinson et al., 2009).

Notably, the increase in patent protection favoring patent owners differed significantly across the circuits (Henry and Turner, 2006; Atkinson et al., 2009; Henry and Turner, 2016). Our theory implies that technology firms would have adjusted the allocation of resources to external and internal R&D across circuits according to changes in the legal protection of patents in the circuits. To identify the effect of patent protection on R&D, we exploit geographical differences in the impact of the CAFC as characterized by Hou et al. (2023b). (Subsequent research by Arque-Castells (2022) applied the same identification strategy.)

Among the several ways in which the technology firm may engage in external R&D, we focus on contract R&D for an external client, using data on public-listed companies (Png, 2019). In such external R&D, the tech firm receives either a share of the client's profit from commercialization or a share of the ownership of the resulting technology. Figure 2 depicts a binned scatter plot of the changes in the numbers of facilities that performed external vis-a-vis internal R&D against the changes in the legal protection of patents as represented by the CAFC index. Evidently, in circuits where patent protection increased to a greater degree, the number of facilities that engaged in external R&D increased relatively more than the number that engaged in internal R&D.

— Figure 2 —

Consistent with Figure 2, regression estimates show that the average change in the legal protection of patents in a circuit due to the CAFC was associated with a 35 percent increase in the number of facilities engaged in external R&D, which was significantly more than the 20.5 percent increase in facilities engaged in internal R&D. The regressions include two-way fixed effects for company interacted with circuit, and so, identify the effect of the CAFC by changes over time within company and circuit. We interpret the empirical results as being due to stronger patent rights increasing the marginal return to external R&D relatively more than the marginal return to internal R&D. Hence, technology firms allocated more R&D resources to external R&D.

The effects of the CAFC on external relative to internal R&D were more pronounced among businesses that were more specialized in technology and less pronounced in industries where patents were more effective in the appropriability of product inventions. These contingency estimates help to validate our interpretation of the regression results as being due to the effect of stronger patent protection on appropriability rather than some confounding factor correlated in time and geography. Our findings are buttressed by multiple robustness checks and estimates ruling out alternative explanations.

The present research calls attention to contract R&D as a service for external clients as a way to exploit technological resources (Cassiman and Veugelers, 2006; Arora et al., 2007; Cassiman and Valentini, 2016; Chen et al., 2020b). Despite the empirical importance of contract R&D (about 46 percent of all companies in our dataset engaged in such), it has received relatively little attention as compared with other modes by which technology firms engage externally, such as joint ventures and alliances (Cassiman and Veugelers, 2002; Hernan et al., 2003). In providing contract R&D, the technology firm accesses new opportunities for profit (mitigating the diminishing marginal return to R&D), but foregoes full ownership of the resulting technology. Our investigation of the sell side of contract R&D complements previous research on the buy side, which focused on the acquisition of knowledge from external sources (Veugelers and Cassiman, 1999; Cassiman and Veugelers, 2002; Arora and Merges, 2004).

Here, we report the first empirical evidence (to our knowledge) on the allocation of limited technological resources between internal and external R&D in response to changes in patent protection. Our research complements previous research that studied the allocation of resources by time horizon (Pennetier et al., 2019; Young et al., 2020), breadth (Klingebiel and Rammer, 2014) and business divisions (Helfat and Maritan, 2023).

In closely related research, contract R&D was positively correlated with the effectiveness of patent protection, but not to a statistically significant degree (Arora et al., 2007). By contrast, we find that stronger patent protection was associated with increases in both internal and contract R&D. Our empirical results are consistent with the customers of contract R&D services looking ahead to commercialization when negotiating with the providers of such services. They differ from those of Arora et al. (2007) possibly because of a larger sample, quasi-experimental design, and more precise measure of patent protection (actual changes in the law rather than reported patent effectiveness). Our research contributes to a more nuanced appreciation of patents as an institution in appropriating the returns from innovation and the market for technology.

More broadly, previous research suggests that, if patent protection is stronger, technology firms should increase external as well as internal R&D (Cassiman and Veugelers, 2002; Hernan et al., 2003; Bhattacharya and Guriev, 2006). Taking this research further, we examine the effect on the allocation of technological resources between internal and external R&D. We highlight the role of diminishing marginal returns to R&D. It is because the marginal return to internal R&D diminishes that the tech firm seeks external R&D. If the marginal return to external R&D diminishes more slowly than the marginal return to internal R&D, then stronger patent protection would induce the firm to allocate relatively more resources to external than internal R&D.

Below, Section 2 presents a case study to illustrate the role of patents in contract R&D for external clients, and Section 3 theorizes how a technology firm should allocate resources between internal and external R&D and adjust to stronger legal protection of patents. Sections 4 and 5 present the empirical strategy and data, Section 6 reports the main and contingency estimates of the effect of the CAFC on external relative to internal R&D. Section 7 concludes with discussion of the implications for policy and management, and directions for further work.

2 Case Study

Laser Technology, founded in 1985 by David Williams, specializes in the development of laser-based systems to measure distance and speed for industrial users. An early success was a system for the U.S. government to measure the distances between two planes while in flight for de-icing. Another was a contract with NASA to measure distances and speeds in space docking missions.[2]

Bushnell produces optical devices for sports and hunting. Historically, rangefinders for professional sport and hunting were the size of a shoe box, weighed about four pounds, required expensive optical lenses, complex electronics, and an external battery, and cost thousands of dollars. In 1994, Bushnell asked Laser Technology to develop a low-cost consumer-oriented laser rangefinder that could be retailed for less than $500.

Laser Technology agreed to develop consumer-oriented rangefinder products below a specific cost point only for Bushnell, and Bushnell agreed to market only Laser Technology products. Each company agreed not to license the technologies to others. Bushnell agreed to pay for the R&D in addition to a royalty on sales.

Chief Technology Officer of Laser Technology, Jeremy Dunne, led the development effort to simplify the lenses and electronics, and reduce the size and weight. Mr Dunne with Stephen Bamberger, an executive of Bushnell, filed patent number 5,926,259 in March 1997, to cover new technologies and assigned it to Bushnell. The new low-cost consumer-oriented rangefinder also applied technologies covered by Laser Technology patents (in-

[2] This case study is based on "Bushnell Files Lawsuit Against LaserTechnology", Photonics.com, April 2022 https://www.photonics.com/Articles/Bushnell_Files_Lawsuit_Against_Laser_Technology/a12289 [Accessed 28 August 2023]; Bushnell, Inc. v. Brunton Co. (D. Kan. 2009) 659 F. Supp. 2d 1150, Civil Action No. 09-cv-2009 KHV/JPO; Bushnell, Inc. v. Brunton Co. (D. Kan. 2009) 673 F. Supp. 2d, 1241 Docket Number: Civil Action No. 09-cv-2009 KHV/JPO; "Brunton Sold to Wyoming Locals", *Outside Business Journal*, 12 November 2021; "Laser Tech: About LTI" and "Executive Bios: Laser Tech" https://lasertech.com/about-lti/ [Accessed 12 August 2022].

cluding number 5,612,779 filed January 1995).

W There were some difficulties in the collaboration. In April 2002, Bushnell sued Laser Technology for failing to provide technical support and over-charging on technology.[3] Still, by 2008, Bushnell had sold two million laser rangefinder units covered by the 5,612,779 and 5,926,259 patents. In that year, Bushnell earned gross revenue of $53 million in the United States, including $11.7 million from sales of its low-end product, the Sport 450, which retailed for $149. Between 1994 and 2008, Bushnell spent over $2.2 million on R&D and paid Laser Technology over $14.6 million in royalties.

In 2008, Brunton, a producer of navigation equipment, introduced a consumer-oriented laser rangefinder, the Echo 440, manufactured by Lanshuo Photoelectric Science and Technology, China. Bass Pro Shop, a major retailer of sporting goods, priced the Echo 440 at $99, causing Bushnell to lose up to $1 million in sales. Bushnell sued Brunton and Lanshuo in the U.S. District Court of Kansas for infringement of the 5,612,779 and 5,926,259 patents. In November 2009, the Court issued an order to enjoin Brunton and Lanshuo from importing and selling the Echo 440 and other infringing Lanshuo products.

Several aspects of this case study are instructive on the management of external R&D. Laser Technology had competencies in laser technologies, particularly relating to rangefinding, and performed R&D to develop products for industrial customers. It contracted to carry out R&D for Bushnell, which produced optical, laser, and electronic devices for amateur sportsmen and hobbyists. Bushnell paid for the R&D and secured a key patent, even naming one of its executives as a co-inventor. The patent was crucial to appropriating the gains from the inventions, enabling Bushnell and Laser Technology to restrain Brunton and Lanshuo from selling competing products. Laser Technology and Bushnell (based in Colorado and Kansas) sued Brunton and Lanshuo (based in Colorado and China) in Kansas, which is in the same 10th federal judicial circuit as Colorado.

[3]We were not able to find the outcome of the litigation, suggesting that the parties settled the case out of court. Yet, this instance illustrates the importance of R&D contracting beyond the assignment of intellectual property rights (Arora et al., 2007).

3 Theory

Referring to Figure 1, consider how a technology firm should allocate limited resources between internal and external R&D. The key difference between internal and external R&D lies in the ownership of the resulting technology. With internal R&D, the tech firm fully owns the resulting technology, which it can commercialize through embedding in products for sale and/or licensing to others. By contrast, with external R&D, the tech firm either receives a share of the client marketing firm's profit contribution, owns a share of the resulting technology, or both.

Then why engage in external R&D? Essentially, the marginal return to R&D diminishes with additional investment (Faff et al., 2013; Curtis et al., 2020). Hence, the tech firm is subject to diminishing marginal returns to internal R&D. Through external R&D, the tech firm accesses a new channel for earnings with a relatively lower dimunition of marginal returns. So, the firm should allocate resources to balance the marginal returns from internal vis-a-vis external R&D. The allocation must also consider that, unlike internal R&D from which the tech firm earns the entire marginal profit contribution from commercializing the resulting technology, the tech firm earns only a fraction of the marginal profit contribution from the external R&D.

Formally, let the tech firm invest Y_i in internal R&D that yields expected profit contribution, $\theta P(Y_i)$. Appropriability, $\theta(\lambda) \in [0, 1]$, is increasing and concave in the degree to which courts interpret the law in favor of patent owners, $\lambda \in [0, 1]$. Concavity of $\theta(\cdot)$ means that the effect of stronger patent protection on appropriability is subject to diminishing returns. Although direct evidence on such diminishing returns is lacking, it seems reasonable that, after some point, increasing patent protection would raise appropriability less than proportionately. The assumption is also consistent with evidence on protection against crime (Gaviria and Pagés, 2002). We assume that the profit contribution, $P(\cdot)$, is increasing and concave, which means that the effect of increasing R&D on profit contribution is subject to diminishing returns (Faff et al., 2013; Curtis et al., 2020).

Besides, the technology firm may also invest Y_e in external R&D which yields profit contribution, $\rho\theta P(Y_e)$, where $\rho \in (0,1)$. This can be interpreted in two ways. One is that the technology produced by the external R&D is owned by a marketing firm which earns expected profit contribution, $\theta P(Y_e)$ and pays a share, ρ, to the tech firm. Another interpretation is that the tech firm owns a share, ρ, of the intellectual property to the technology, and earns directly from commercialization (Arora et al., 2007). Of note, the tech firm's R&D investment, Y_e, is not contractible (Lee and Png, 1990), and so, the tech firm cannot be directly compensated for the external R&D.[4]

Let the cost of R&D be $C(Y_i + Y_e)$, which is increasing and convex. Convexity means that the marginal cost of R&D increases with additional R&D. (The theory is quite general and also applies to the specific case of fixed resources, $Y_i + Y_e \leq \bar{Y}$, for some $\bar{Y}$.)

We stipulate that the firm chooses Y_i and Y_e to maximize expected profit

$$\Pi = \theta P(Y_i) + \rho\theta P(Y_e) - C(Y_i + Y_e). \tag{1}$$

The first-order condition with respect to internal R&D is

$$\frac{\partial \Pi}{\partial Y_i} = \theta \frac{dP}{dY_i} - C' = 0, \tag{2}$$

which implies that the profit-maximizing level of internal R&D is

$$Y_i^*(\lambda) = \frac{\partial P}{\partial Y_i}^{-1} \left(\frac{C'}{\theta} \right) = \Psi \left(\frac{C'}{\theta} \right), \tag{3}$$

where Ψ represents the inverse of the marginal profit function. Similarly, the first-order condition with respect to external R&D is

$$\frac{\partial \Pi}{\partial Y_e} = \rho\theta \frac{dP}{dY_e} - C' = 0, \tag{4}$$

[4] The theory is parsimonious in stipulating the same functional forms of appropriability and profit contribution for both internal and external R&D. Hence, the propositions do not depend on idiosyncratic differences between internal and external R&D in appropriability and profit contribution.

which implies that that the profit-maximizing level of external R&D is

$$Y_e^*(\lambda) = \Psi\left(\frac{C'}{\rho\theta}\right). \tag{5}$$

By (2) and (4), at the profit maximum, the technology firm should equalize the marginal profit contributions from internal and external R&D,

$$\theta\frac{dP}{dY_i} = C' = \rho\theta\frac{dP}{dY_e}. \tag{6}$$

The above implies that

$$\frac{dP}{dY_i} = \rho\frac{dP}{dY_e} < \frac{dP}{dY_e},$$

as $\rho < 1$.

Essentially, engaging in external R&D involves a fundamental trade-off between accessing a new channel of earnings to balance the diminishing marginal return to internal R&D but is less profitable because it yields only a fraction of the additional profit contribution generated. Hence, the tech firm should invest in both internal and external R&D, but more in the former.[5] (Please refer to Appendix A for the formal propositions on which this and the following results are based.)

Hypothesis 1 *The technology firm should carry out more internal R&D than external R&D,* $Y_i^* > Y_e^*$.

Our research question is how the tech firm should adjust the allocation of resources to internal and external R&D in response to changes in the legal protection of patents, λ. To align with the empirical Poisson model of the number of facilities, we consider the proportionate effects on internal and external R&D. An increase in the legal protection of patents would strengthen the appropriability of the returns to both internal and external

[5]This theoretical setup implicitly stipulates that the tech firm has the resources required to commercialize internal R&D as well as perform R&D for external clients. Our theory does not apply to businesses that specialize in either internal or external R&D, and so, do not face the issue of allocating resources between internal and external R&D.

R&D, and so, raise the expected returns to both. Whether the tech firm should increase internal R&D or external R&D relatively more depends on the extent of the diminishing marginal returns to each type of R&D, or formally, how concave is the function, $P(\cdot)$.

Intuitively, the tech firm would adjust external R&D according to the effect of the stronger patent protection on the marginal return to external R&D, and similarly adjust internal R&D according to the effect on the marginal return to internal R&D. By Hypothesis 1, external R&D is less than internal R&D, hence, the marginal return to external R&D would exceed that to internal R&D. However, the effect of the stronger patent protection on the marginal returns depends on the rate at which the marginal returns diminish with additional R&D. A sufficient condition for the tech firm to adjust external R&D relatively more is that the marginal return to external R&D diminishes more slowly than the marginal return to internal R&D. Essentially, the condition is that the rate at which marginal returns to R&D diminish be moderate.

Hypothesis 2 *Suppose that the marginal return to external R&D diminishes more slowly than the marginal return to internal R&D. Then, if the legal protection of patents is stronger, the technology firm should increase external R&D relatively more than internal R&D.*

Empirically, it is challenging to directly observe the degree of diminishing marginal returns to R&D. A plausible indirect measure is the extent to which the tech firm diversifies its technology. To the degree that it encounters diminishing marginal returns in its main field of technology, the tech firm would increase profit by diversifying into other fields (Simonen et al., 2015; Sohl et al., 2022). Accordingly, we reason that the degree of diminishing marginal returns would be correlated with the degree of technology diversification. Businesses whose marginal returns diminish more slowly would be more specialized. Thus, we posit that

Hypothesis 3 *If the technology firm is more specialized in technology, the effect of stronger legal protection of patents on the increase in external relative to internal R&D would be amplified.*

Finally, we study the effectiveness of patents in appropriability as a contingency in the effect of stronger legal protection of patents on external relative to internal R&D. If patents are more effective in appropriability, then the effects of stronger legal protection of patents on both external and internal R&D would be *attenuated*. The reason for this somewhat paradoxical result is that, if patents are more effective in appropriability, the profit-maximizing levels of internal and external R&D would be higher. As the marginal return to R&D is diminishing, the effect of stronger patent protection at those higher levels of internal and external R&D would be less.

To reiterate, if patents are more effective in appropriability, each of the effects of stronger patent protection on external and internal R&D would be attenuated. Yet, provided that stronger legal protection leads the tech firm to increase external R&D relatively more than internal R&D (Hypothesis 2), the difference between the increases in external R&D vis-a-vis internal R&D would also be attenuated. This reasoning leads to

Hypothesis 4 *If patents are more effective in appropriability, the effect of stronger legal protection of patents on the increase in external relative to internal R&D would be attenuated.*

4 Empirical Strategy

We aim to investigate the effect of stronger legal protection of patents on the allocation of limited technological resources between internal and external R&D. The empirical challenge is to identify an exogenous change in patent protection.

Our approach is to exploit the assumption of jurisdiction over patent appeals by the U.S. Court of Appeals for the Federal Circuit (CAFC). Patents being a matter of federal jurisdiction, disputes are litigated in federal courts, with district courts being the court of first instance. Prior to the CAFC, patent disputes originating in district courts were appealed to regional Circuit Courts of Appeal. The Circuit Courts varied systematically in the rate at which they found patents to be valid and infringed (Henry and Turner, 2006; Atkinson et al., 2009).

In October 1982, the U.S. Congress established the CAFC to unify appeals and harmonize the interpretation of the law. Through a series of major decisions between 1982-1985, the CAFC shifted the law, mostly in favor of patent owners (Dreyfuss, 1989; Seamon, 2003; Atkinson et al., 2009). Despite the efforts to harmonize, the post-CAFC interpretation of the law varied across the circuits (Hou et al., 2023b). Given the prior differences in the circuits and incomplete harmonization, the CAFC changed the legal protection of patents to different degrees in the various circuits (Henry and Turner, 2006; Atkinson et al., 2009; Henry and Turner, 2016).

To represent geographical variation in the strengthening of legal protection due to the CAFC, Hou et al. (2023b) constructed an index by regressing patent litigation outcomes on circuit fixed effects before and after the CAFC assumed jurisdiction over patent appeals. The estimates controlled for patent and litigation characteristics. In Appendix B, Table B1, columns (a) and (b), report the degree to which court rulings favored patent owners before and after CAFC respectively. Table B1, column (c), presents the CAFC index, which represents the shift in favor of patent owners due to the CAFC. Apparently, the CAFC strengthened the legal protection of patents in all but the 10th and 11th Circuits, where they were already well protected before the CAFC.

To interpret the CAFC index, consider litigation in which the owner of a patent with the average number of claims, 13, sued for infringement in the 6th Circuit. The 6th Circuit experienced the average increase in the legal protection of patents due to the CAFC. Then, comparing the litigation outcomes before and after the CAFC, the likelihood of the patent being invalidated fell by 31 percent and the likelihood of the patent being judged to be valid and infringed rose by 45 percent.[6]

Importantly, in circuits where the legal protection of patents increased to a larger extent, both the rate of appeals and stock market value of patents increased relatively more (Hou et al., 2023b). These results support the inference that the timing of the

[6]These statistics are based on the likelihoods of the respective outcomes as predicted by the ordered logit regression. Pre-CAFC, the likelihood of the patent being invalidated was 0.449, valid but not infringed was 0.236, and valid and infringed was 0.31. By contrast, post-CAFC, the likelihoods were respectively, 0.31, 0.236, and 0.449.

CAFC assumption of jurisdiction and direction of its rulings were plausibly exogenous. Accordingly, we exploit the CAFC as a quasi-natural experiment to investigate the effect of stronger legal protection of patents on the allocation of resources to external R&D.

Consider the following model of resources allocated to R&D for internal use or external clients by company i in circuit c in year t,

$$E(Y_{ict} \mid X_{ict}) = \exp(\beta \text{ CAFC}_c \cdot \text{Post}_t + \beta_X X_{it} + \alpha_{ic} + \alpha_t). \tag{7}$$

In (7), Y_{ict} is a measure of R&D resources, CAFC_c is the constructed CAFC index representing the shift of the legal protection of patents due to the CAFC by circuit. Post_t is an indicator of observations in the post-CAFC era, X_{it} are time-varying company controls, and α_{ic} and α_t are company-circuit and year fixed effects. The coefficients to be estimated are those of the CAFC, β, and the controls, β_X.

Implicitly, our empirical strategy stipulates that companies decentralized the administration of R&D, particularly the allocation of resources between internal and external R&D, guided by the interpretation of patent law in the circuit ("home circuit assumption"). Prior research into knowledge sourcing, mergers and acquistions, and patenting also stipulated that companies decentralized their innovation strategy by geography (Arora et al., 2014; Seru, 2014; Hou et al., 2023a).

The home circuit assumption provides that patents are enforced in the jurisdiction where R&D is performed. The geographical distribution of the assignment of patents provides some evidence for the assumption. In our sample, in the circuits in which a company engaged in internal R&D, the company was assigned one or more patents in 64 percent of the circuits. The proportion for external R&D was 63 percent. Relaxing the home circuit assumption should not invalidate our empirical strategy to the extent that the relevant patents were assigned to the unit which performed the R&D.

Moreover, almost half of patent cases were indeed tried in the home circuit (Hou et al., 2023a), which is consistent with the home circuit assumption. Compared to other venues, the home circuit offers lower cost of litigation and possibly some advantage (Atkinson et al., 2009). Further, violation of the home circuit assumption would result in the estimated coefficient of the CAFC index being attenuated. Still, in supplementary estimates, we examine the sensitivity of our results to the home circuit assumption.

The specification (7) includes two-way fixed effects for companies interacted with circuits and fixed effects for years. The company-circuit fixed effects control for non-time-varying differences between companies in their propensity to carry out R&D by circuit. In particular, the company-circuit fixed effects absorb time-invariant factors that affect the tendency of each company to perform internal or external R&D in the respective circuit. Hence, the estimated effect of patent law, β, is identified by exogenous changes in the legal protection of patents due to the CAFC in the circuit. The year fixed effects abstract the analysis from any general economy-wide changes in internal and external R&D.

Our data on R&D resources are the numbers of R&D facilities. As these are counts, we apply Poisson regression to estimate (7) separately on internal and external R&D to obtain the coefficients, β_i and β_e. The coefficient, β_i, characterizes the proportionate change in the number of internal R&D facilities associated with a unit increase in patent protection due to the CAFC, and likewise, β_e for external R&D.

Then, to examine the effect of the CAFC on external relative to internal R&D, we test the significance of the difference in the coefficients, $\beta_e - \beta_i$ based on permutation tests.[7] The errors in the regression models for observations of the same company or in the same circuit might be serially correlated. Hence, we estimate standard errors that are robust to heteroskedasticity and clustered two-way by company and circuit. As the number of clusters is just 11, the standard diagnostic tests would tend to over-reject (Kezdi, 2004), and accordingly, we report bootstrapped standard errors clustering by company and circuit.

[7]The permutation test consists of generating a bootstrapped sample of 1,000 repetitions with the numbers of facilities in each circuit engaged in external and internal R&D randomly drawn without replacement from the true numbers. Then, we calculate the likelihood of observing our estimated coefficients in the distributions of the 1,000 bootstrapped estimates.

5 Data

For empirical analysis, we require data by business and its location on the allocation of resources between internal and external R&D. We draw on the Cattell directories, which aimed to report all nongovernment facilities engaged in commercially applicable basic and applied research within the United States. We supplement the Png (2019) dataset for nine years in the period 1975-97 with new data for the year 1977 to improve the pre-CAFC coverage.[8]

The Cattell directories published detailed information about the facilities at which each firm performed R&D, including parent company, location, number of R&D staff, and purposes of the R&D. Up to 1979, the purposes were recorded in the four categories, "R&D for the parent organization", "Contract R&D for others", "Consultation for others", and "Testing and analysis for others".[9] From 1981, the categories were revised to: "R&D for parent organization", "On contract for industry", "On contract for government", and "Consultation for others".

Motivated by the Laser Technology case study above, we deem "Contract R&D for others", "contract for industry", and "Consultation for others", and "Testing and analysis for others" to mean the conduct of R&D on a contract basis for the benefit of an external client. Referring to our theory, contract R&D for external clients is one form of "external R&D", in contrast to "internal R&D" (classified by Cattell as "R&D for parent organization").[10] In the following narrative, we simply refer to contract R&D for external clients as external R&D.

We match the Cattell data by parent company and year to financial information in

[8]The Cattell data seemed to be the most appropriate. Contracts would reveal external R&D but not R&D for internal users, as the latter would not be governed by contract. Both internal and external R&D might evince in patents, but the patents would not reveal the contractual relationship among the employers of the inventors.

[9]Actually, in the 1979 edition, the first category was defined more narrowly as "R&D for the parent organization only". However, earlier and later editions did not use the qualifier "only". Moreover, empirically, among the facilities which reported performing R&D for the parent organization, about 23 percent also reported performing R&D for others. Accordingly, we ignore the "only" as a once-only aberration.

[10]We consulted the publisher as well as scholars who used the Catell directories in previous research, but could not procure the original questionnaire on which the directories were based.

Compustat, using the Png (2019) correspondence. Further, we focus on manufacturing industries and exclude defense businesses (SICs 348 and 376) as their R&D strategy might differ from those that sell to commercial businesses. The inclusion criteria yield a sample comprising 10,504 company-circuit-year observations, consisting of 1,321 unique companies.

Appendix C, Table C1, reports the distribution of the sample by industry. The largest representations were from chemicals (17.3 percent), electronics and electricals (14.9 percent), closely followed by computer equipment (13.7 percent) and instruments (13.2 percent). The average company operated 1.03 facilities per circuit across two circuits per year, with 0.94 facility engaged in internal R&D and 0.32 facility in contract R&D for external industry clients. Of the 1,321 companies in our sample, 676 had at least one facility engaged in external R&D. Apparently, external R&D was quite common.

Then, we merge the company-circuit-year panel with the CAFC index by circuit and year. Since the CAFC issued the key precedents in favor of patent owners between 1982-1985, we exclude the years in that period covered by the Png (2019) dataset (1983 and 1985) from the sample. Table 1, Panel A, summarizes the company-circuit-year sample. Before the establishment of the CAFC, the average number of R&D facilities by company-circuit was 1.08, which fell to 1.00 after the CAFC. This overall decline is consistent with previous research on industrial R&D (Arora et al., 2020). Meanwhile, the number of facilities that performed internal R&D per company-circuit fell from 1.03 to 0.88, and the number of facilities that performed external R&D fell from 0.34 to 0.31.

A limitation of the Cattell dataset is that, for facilities that carried out both internal and external R&D, it does not reveal the division of resources between the two segments. Assuming that the CAFC did not affect the division of resources within such facilities, the error in representing resources by the number of facilities is classical, and would only inflate the standard errors of the estimates without affecting consistency. Importantly, the estimate of the difference in the effects on internal and external R&D would also be consistent. Appendix D presents additional discussion of error in measurement of R&D resources. In particular, it reports supplementary estimates which show robustness to the definitions of internal and external R&D and that representing technological resources by the count of facilities yields conservative findings.

Following prior research (Hall and Ziedonis, 2001; Aghion et al., 2013; Gibbs, 1993; Chen et al., 2020a), our regression analyses control for size (total number of employees), revenue per employee, PPE (property, plant, and equipment) per employee, and cash flow per employee. These controls abstract the analyses from the effects of company size, profitability, and manufacturing assets on the technological resource allocations to different R&D. We winsorize the financial data at the 1st and 99th percentiles, and specify covariates that might be zero (employees, revenue, PPE, EBITDA, and R&D expenditure) in inverse hyperbolic sine, as these are defined in non-positive values (Bellemare and Wichman, 2020). Table 1, Panel B, presents operational and financial characteristics of the companies. Post-CAFC, on average, companies employed fewer people, but earned higher revenue per employee, and invested more in R&D.

– Table 1 –

6 Estimates

We first examine the proposition that technology firms should allocate more resources to internal than external R&D (Hypothesis 1). Referring to Table 1, Panel A, one-sided t-tests suggest that the mean of external R&D is less than the mean of internal R&D both before and after the CAFC. More broadly, Figure 3 plots the kernel densities of the distributions of internal and external R&D. By a one-sample Kolmogorov-Smirnov test, the null hypothesis of identical distributions is rejected ($p < 0.001$).

– Figure 3 –

Next, consider our main research question – how did the change in the legal protection of patents due to the CAFC (mostly in favor of patent owners) affect the allocation of resources between internal and external R&D among technology firms? Recall Figure 2, the binned scatter plot of the relation between the changes in the numbers of facilities engaged in internal and external R&D and the changes in the legal protection of patents due to the CAFC (CAFC index). Evidently, in circuits where the law shifted relatively more in favor of patent owners, companies were more likely to raise both internal and external R&D. Further, comparing the slopes of fitted lines suggests that the CAFC was related to a more pronounced increase in external R&D facilities relative to internal R&D facilities. The binned scatter plots yield preliminary support for Hypothesis 2 that stronger patent protection would induce the tech firm to increase the allocation of resources to external R&D relative to internal R&D.

While intuitive, Figure 2 is based on highly aggregated data and the observed pattern might be due to spurious correlation, such as the development of technologies concurrent with the establishment of the CAFC. To investigate more rigorously, we turn to multiple regression analysis, which controls for other factors that might possibly confound the relation between R&D and the CAFC. Table 2 reports regression estimates of (7) by quasi-maximum likelihood with the dependent variable specified as, for each company-circuit-year, the number of facilities. We estimate using Stata routine, ppmlhdfe, which drops observations that are either singletons or separated by the company-circuit fixed effect (Correia et al., 2020). Thus, the number of observations would vary with the dependent variable and differ across specifications.

– Table 2 –

Referring to Table 2, column (a), in the estimate of all facilities, the coefficient of the CAFC index, 0.330 (s.e. 0.112) is positive. This result is consistent with stronger patent protection in a circuit increasing the appropriability of R&D and so, inducing technology firms to invest resources and set up more facilities in that circuit. In the estimate of external R&D facilities (Table 2, column (b)), the coefficient of the CAFC index, 0.497 (s.e. 0.204), is positive, consistent with stronger patent protection inducing more external R&D facilities. The results for internal R&D (Table 2, column (c)) are qualitatively similar.

To examine the allocation of resources, we consider the economic effect of the CAFC at the average increase of patent protection measured by the CAFC index (0.603). Referring to Table 2, columns (a)-(c), the CAFC was associated with 0.20 more facility overall (22 percent increase above the pre-CAFC level), 0.20 more facility engaged in external R&D

(35 percent increase), and 0.18 facility engaged in internal R&D (20.5 percent increase). Importantly, the effect of the CAFC on external R&D was more pronounced than on internal R&D (permutation test of the coefficient of CAFC on external R&D minus the coefficient of CAFC on internal R&D, 0.188 ($p = 0.002$)). This result is consistent with Hypothesis 2 that stronger patent protection would increase the allocation of resources to external R&D relative to internal R&D.

Changes in the legal protection of patents might affect a technology firm's expenditure on R&D, and thereby, its technological capability and engagement in external R&D. To examine this channel, Table 2, columns (d)-(f), report estimates including controls for R&D expenditure and an indicator of no reported R&D (Koh et al., 2022). The coefficients of the CAFC are about the same as in the estimates without control for R&D. Still, these estimates should be interpreted with caution as R&D is endogenous to changes in the legal protection of patents. Subject to that proviso, we interpret the estimates as suggesting that the CAFC affected the allocation of technological resources to internal and external R&D directly rather than through any increase in investment in R&D.[11]

Taken together, the estimates suggest that, to the extent that the CAFC increased the legal protection of patents in a circuit, businesses allocated relatively more resources to external as compared with internal R&D. We interpret the results as due to stronger patent protection increasing appropriability, and raising the marginal return to external R&D relatively more than the marginal return to internal R&D. By Hypothesis 2, stronger patent protection would increase external relative to internal R&D if the rate of diminishing marginal returns to R&D is moderate. Accordingly, our estimates are consistent with moderately diminishing marginal returns to R&D.

[11]It might seem puzzling that the resources for both internal and external R&D could increase with control for overall R&D expenditure. A major reason must be that external R&D is separately accounted. For instance, KVH Industries disclosed that "customer-funded research and development are not included in the research and development expense" (Form 10-Q, 27 April 2020, page 29).

6.1 Contingencies

Our main results show that stronger patent protection increases external R&D more than internal R&D. This observation implies that, in our sample, marginal returns diminished at a moderate rate. Besides the main effect, we are also interested in how the effect of patent protection might vary with characteristics of the firm and industry. These contingency analyses serve to validate our interpretation of the effect of the changes in the law and also yield useful managerial implications.

Consider first the degree to which the tech firm specializes. Hypothesis 3 operationalizes the rate of diminishing returns to R&D by the degree of technological diversification, and posits that, among more specialized firms, the effect of the CAFC would be amplified. To investigate, we measure specialization using the number of technology fields as recorded in the Cattell dataset (Png, 2019). (In the sample, the average company engaged in 4.53 fields, examples of which are sonar, refrigeration, and immunology.) A company that carries out R&D across more fields is deemed to be less specialized.

– Table 3 –

We re-estimate (7), splitting the sample by whether the company specialized more or less than the industry (3-digit SIC) median. Table 3, columns (a)-(d), present the results. Among more specialized companies, the CAFC was associated with a larger increase in external than internal R&D ($p = 0.003$). By contrast, among less specialized companies, the CAFC did not differ in effects on external vis-a-vis internal R&D ($p = 0.48$). The differences in how CAFC affected external vis-a-vis internal R&D between more and less specialized firms is significant ($p = 0.024$).

We interpret these results as consistent with Hypothesis 3 that the effect of stronger legal protection of patents on the allocation of resources to external relative to internal R&D would be amplified among more specialized firms. These results are also consistent with the argument that diminishing returns to R&D lead the firm to diversify fields of technology.

Next, consider the effectiveness of patents in appropriability, which is an important factor in innovation strategy and market for technology (Cohen et al., 2000; Arora and Gambardella, 2010). Hypothesis 4 posits that, if patents are more effective, the effect of stronger legal protection on the allocation of resources towards external R&D relative to internal R&D would be attenuated. To investigate, we apply the Cohen et al. (2000) measures of patent effectiveness, and split the sample by industry, according to the median patent effectiveness for new products or new processes.

Referring to Table 4, columns (a)-(b), in industries where patents were more effective in the appropriability of new product inventions, the effect of the CAFC on external and internal R&D was not much different ($p = 0.376$). By contrast, referring to Table 4, columns (c)-(d), in industries where patents were less effective in appropriability of new product inventions, the CAFC had a larger effect on external than internal R&D ($p = 0.017$). Importantly, consistent with Hypothesis 4, the effect of the CAFC on external relative to internal R&D was more pronounced in industries where patents were less effective ($p = 0.059$).

– Table 4 –

Referring to Table 4, columns (e)-(h), the results were qualitatively the same but statistically less precise in the comparison between industries where patents were more or less effective in the appropriability of new process inventions. The imprecision might be due to patents being generally less effective than trade secrecy in the appropriability of process inventions (Ganglmair and Reimers, 2019).

6.2 Validation

The CAFC issued key precedents on patent law between 1982-1985. To validate our empirical strategy, we carry out an event study in which the change in the legal protection of patents due to the CAFC is stipulated hypothetically to have been effective in each of the years 1975-1997, excluding 1981 as the reference year. We then estimate (7) with the legal protection of patents represented by interactions between the CAFC index by circuit with each of the hypothetical effective years.

– Figure 4 –

Referring to Figure 4, Panel A, for external R&D, the coefficient of the placebo oscillates from 1975 to 1979, then increased sharply in 1983 and is elevated in the following years. The trajectory is similar for internal R&D (Figure 4, Panel B). Apparently, the CAFC was associated with increases in both external and internal R&D between 1981-1983. Figure 4 does not evince any pre-trends and supports our stipulation that the increase in the legal protection of patents due to the CAFC was exogenous.

In another validation exercise, we estimate the effect of the CAFC on R&D for the government. Tech firms may engage in R&D for the government, which produces technology that can possibly be commercialized. Government R&D is similar to external R&D (more precisely, contract R&D for external clients to the extent that it draws on the firm's limited technology resources and the firm gets partial ownership of the resulting technology). Then, the firm should adjust the allocation of resources to government R&D similarly to external R&D. Appendix E, Table E1, column (a), reports the results. Consistent with our reasoning, the change in government R&D did not differ from that in external R&D ($p = 0.135$), whereas it did differ from that in internal R&D ($p < 0.001$).

Recall that our empirical strategy was based on the home circuit assumption that businesses allocate resources on a regional basis guided by the courts' interpretation of the law in the region. Alternatively, it might be argued that companies make strategic R&D decisions at headquarters, guided by the interpretation of the law in the headquarters region.

To examine this challenge to our empirical strategy, we assembled a company-year panel with R&D resources aggregated to the company level and matched to the CAFC index in the federal judicial circuit of the company headquarters. Appendix E, Table E1, columns (b) and (c), report the estimates of (7) on the company-year panel. For both external and internal R&D, the coefficients of the CAFC index and estimated economic effects are smaller and less precise than the preferred estimates based on the home circuit assumption (Table 2, columns (b) and (c)). The attenuation in the estimates based on headquarters strategy is consistent with the actual locus of strategy being regional, resulting in measurement error. Still, regarding our main research question, even the estimates based on headquarters strategy are consistent with the CAFC increasing external R&D more than internal R&D ($p = 0.025$).

6.3 Forum shopping

Appendix F presents supplementary estimates to check the sensitivity of our findings to possible forum shopping, which would challenge the home circuit assumption. The first applies a weighted CAFC index which takes account of the likelihood of litigation in other circuits (Hou et al., 2023b). Referring to Table F1, column (a), the coefficient of the alternative CAFC index is 0.672 for external R&D and 0.573 for internal R&D. These estimates are respectively more than one-third and three-quarters larger than the estimated coefficients using the original CAFC index (Table 2, columns (b) and (c)). These differences are consistent with the home circuit assumption over-estimating the changes in patent protection, and so, under-estimating the effects of the CAFC on external and internal R&D.

A weakness of the weighted index is that it is based on the aggregate rate of litigation outside the home circuit and does not account for each individual company's likelihood of forum shopping. Next, we construct two firm-specific indexes that exploit the law on judicial forum. Until October 1990, when the CAFC changed the law, patent cases had to be filed at the location of the defendant (Chien and Risch, 2017). Hence, until then, businesses could only choose to litigate outside their home circuit to the extent that their competitors were located elsewhere.

We define competitors as other businesses whose patents cited the focal firm, and characterize the likelihood of litigation in the home circuit as the proportion of competitors located in the home circuit and the likelihood of forum shopping as the proportion of competitors located in other circuits. We then construct the home circuit CAFC index as the product of the original CAFC index and the likelihood of litigation in the home circuit, and similarly for the forum shopping CAFC index.

Table F1, columns (b) and (c), present the estimates. Regardless of whether the potential infringer was located in the home circuit of the subject company or in another circuit, the CAFC had a more pronounced effect on external as compared with internal R&D. We interpret the results as due to stronger legal protection of patents leading the tech firm to allocate more resources to external relative to internal R&D.

Finally, Table F1, columns (d) and (e), report two additional checks of robustness to forum shopping. Taken together, the estimates reported in Appendix F suggest that our finding that the CAFC was associated with the allocation of resources towards external R&D relative to internal R&D is not sensitive to the home circuit assumption.

6.4 Alternative Explanations

The present research is a retrospective study of archival data, and the positive relation between the CAFC and the increase in external relative to internal R&D might be explained in other ways besides the increase in the appropriability of returns in external relative to internal R&D. One alternative explanation is that stronger patent protection reduced the potential loss from leakage of proprietary knowledge to external parties, and so, induced the technology firm to engage in more external R&D (Cohen et al., 2000; Ceccagnoli, 2009; Kang and Lee, 2022). Rather than affecting resource allocation through the marginal returns to investments in future technologies, changes in patent protection affected resource allocation through the appropriability of existing technologies.

To investigate this theory, we compare the impact of the CAFC on internal and external R&D by the risk of misappropriation, as represented by the percent of competitors located in the home circuit (as constructed in our investigation of forum shopping). Businesses that face higher misappropriation risk should increase external R&D more than those which face lower risk. Referring to Appendix G, Table G1, columns (a) and (c), the coefficient of the CAFC index in external R&D is 0.650 (s.e. 0.650) among businesses which faced higher risk and 0.378 (s.e. 0.225) among businesses which faced lower risk. Although the difference in the coefficients is consistent with the misappropriation narrative, it lacks precision ($p = 0.183$), and so, we still prefer the interpretation in terms of the appropriability of future R&D.

Another alternative explanation is that patent protection increases external R&D by reducing the extent to which the tech firm could hold up the client by re-developing similar technology for others (Bhattacharya and Guriev, 2006). Then, the effect of stronger patent protection on external R&D should be attenuated among tech firms with good reputation among potential clients. To examine this narrative, we reason that engagement in external R&D is itself concrete evidence of good reputation. Table G1, columns (e)-(h), report estimates for companies by pre-CAFC engagement in external R&D. Contrary to the alternative explanation, the effect of the CAFC on external R&D was more pronounced among companies that were more engaged in external R&D pre-CAFC.

7 Discussion

Here, we analyze theoretically how a technologically capable firm should allocate limited resources to external and internal R&D. To maximize profits, it should equalize the marginal returns from external and internal R&D. This means balancing two factors: on the one hand, external R&D provides another channel for profit, thus mitigating diminishing marginal returns to internal R&D, but on the other hand, the tech firm earns only a fraction of the profit generated by the external R&D.

The theory provides guidance on how to adjust the allocation of resources to an increase in appropriability. Generally, increased appropriability would raise the returns to both external and internal R&D. If the marginal return to external R&D diminishes at a lower rate than the marginal return to internal R&D, then, if appropriability increases, the tech firm should increase the allocation of resources to external R&D relatively more than internal R&D. (To be parsimonious, the theory stipulates the same functional form for the profit contribution of external and internal R&D. Hence, formally, the condition that the marginal return to external R&D diminish more slowly than the marginal return to internal R&D is equivalent to the marginal return to R&D diminishing at a moderate rate.)

This theory is quite general and applies to all forms of external R&D including contract R&D (the focus of our empirical study), collaboration, and joint ventures, and all ways by which appropriability might increase including stronger legal protection of patents (the focus of our empirical study), better institutions, and more effective relational mechanisms.

In the empirical study, we applied an index that represents exogenous regional differences in the increase of the legal protection of patents due to the establishment of the CAFC. We find that stronger legal protection of patents due to the CAFC was associated with a more pronounced increase in external R&D as compared with internal R&D. We interpret the difference as due to allocation of resources towards external R&D. The effect of stronger patent protection on resource allocation was attenuated in industries where patents were more effective in appropriability of the returns to product innovations, and amplified among firms that were more specialized in technology.

Based on our theoretical analysis and empirical findings, we offer guidance on several aspects of the management of innovation. Previous research on the commercialization of technology emphasized the trade-off between the revenues from licensing and the reduction in sales revenue due to increased product competition (Arora and Fosfuri, 2003; Fosfuri, 2006). Here, we show that, in R&D, the decision to open up knowledge boundaries of the firm to serve external clients also involves a trade-off. Accessing a new channel of earnings mitigates the diminishing marginal return to internal R&D, but yields only a fraction of the earnings generated. Given limited R&D resources, the allocation of these resources is strategic, and managers should plan internal and external R&D jointly. Further, policy makers should formulate innovation policies to encompass both internal and external R&D, rather than either in isolation.

Second, we showed that stronger legal protection of patents was associated with an increase in external relative to internal R&D. We interpreted this result as due to the increase in appropriability raising the marginal return to external R&D relatively more than the marginal return to internal R&D. The key to the analysis is not the marginal returns as such but the rate at which they diminish with additional R&D. In allocating scarce technology resourcs, businesses must pay attention to both the marginal returns and the rate of diminishing marginal returns.

Prior research into R&D has found diminishing returns at the company level (Faff et al., 2013; Curtis et al., 2020). Our empirical results go further to (implicitly) show diminishing returns within companies by geography, and that the rate of diminution is moderate. This provides some comfort to managers in budgeting for future R&D expenditure.

Third, how to adjust the allocation of resources between external and internal R&D in response to stronger legal protection of patents varies with the degree of specialization in technology and the effectiveness of patents in appropriability. For businesses that are more specialized in technology, stronger patent protection increases the marginal return to external R&D more than internal R&D. This sheds light on the research about exploration and exploitation as well. Follow-up research might delve deeper into whether resources allocated to external clients might lead to more diversified and explorative technologies. Seemingly paradoxically, in industries where patents are more effective in appropriability, businesses should adjust the allocation of resources between external and internal R&D relatively less. The reason is that, in those industries, the resources allocated were already high, and so, changes in patent protection would have relatively less effect.

Our findings are subject to several limitations. One is that the coverage of the Cattell data ended in 1997. Still, it is reasonable to think that the issue of allocating resources across the boundary of the firm between internal and external R&D continues to be relevant. We searched the U.S. Securities and Exchange Commission archive for R&D contracts and manually read the first 43 which involved commercial parties and governed R&D (Appendix H). Of those, 16 governed R&D as a service by one party for the benefit of another which is the subject of our study, among which the client owned the resulting technology in 11, and jointly owned the technology with the R&D provider in the other 5.

Another limitation is that our sample comprised publicly listed companies for which Compustat reports financial and operational information. These tend to be larger than private businesses. The strategic considerations for smaller businesses may differ, for instance, they might specialize in external R&D (Arora and Merges, 2004; Arora et al., 2020). We did find that the CAFC had a more pronounced effect on the allocation of resources between internal and external R&D among larger companies, which might suggest that the effects of stronger patent protection might be weaker among private businesses.

Third, our empirical analysis relied on observational data around the CAFC assuming jurisdiction over patent appeals. We interpret the more pronounced increase in external R&D relative to internal R&D as due to the increase in appropriability coupled with the marginal return to external R&D diminishing more slowly than the marginal return to internal R&D. The data rule out two alternative explanations. However, we cannot definitively rule out some other mechanism that varied by region and time similarly to the CAFC.

Finally, the quasi-natural experiment engendered by the CAFC took place in the early 1980s. Yet, the underlying theoretical principles are enduring. Businesses need to allocate limited resources across multiple dimensions, one of which is to internal use vis-a-vis external clients. Stronger patent protection may affect the appropriability of external vis-a-vis internal R&D differently, and businesses should re-allocate resources accordingly. Patent law continues to evolve. For instance, H.R.5874 "Restoring America's Leadership in Innovation Act of 2021", 117th Congress (2021-2022), proposed to strengthen patent protection. Our theoretical analysis provides guidance to managers and policy-makers on the implications of such laws for the allocation of limited R&D resources.

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Figure 1. Innovation timeline

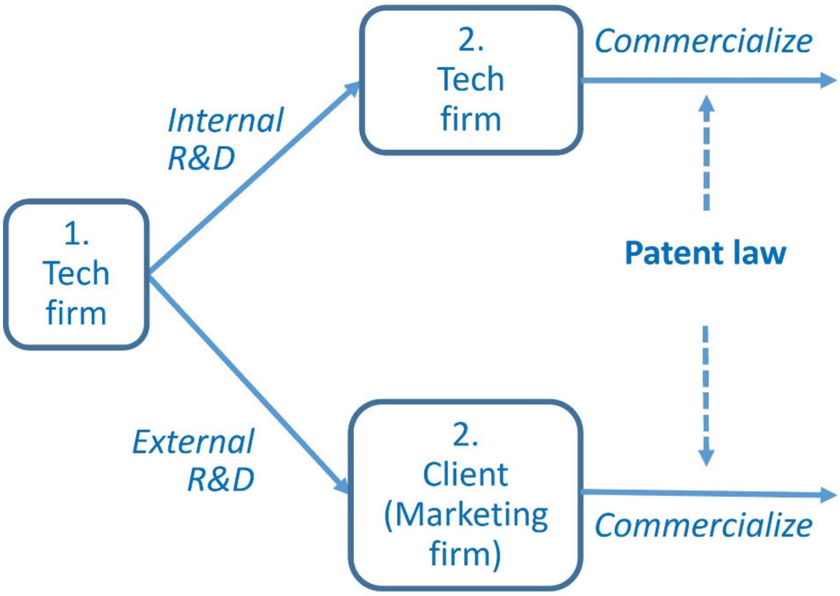
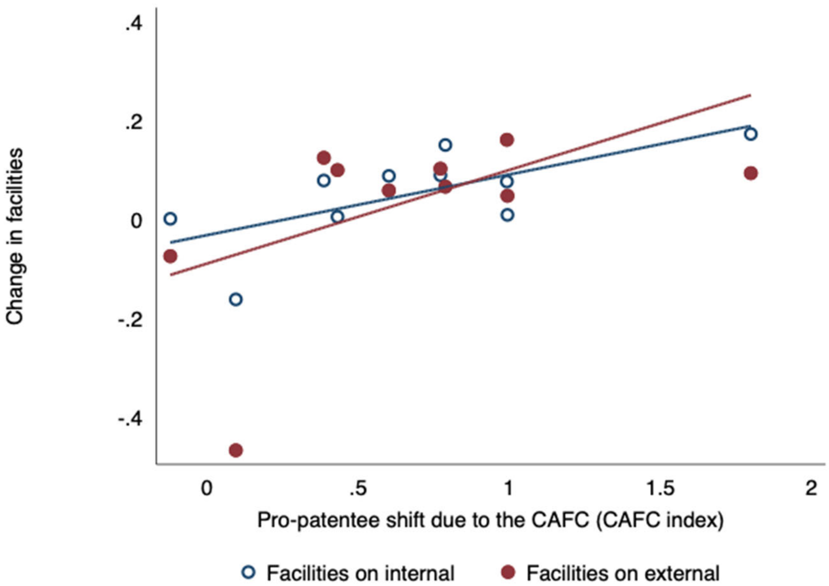
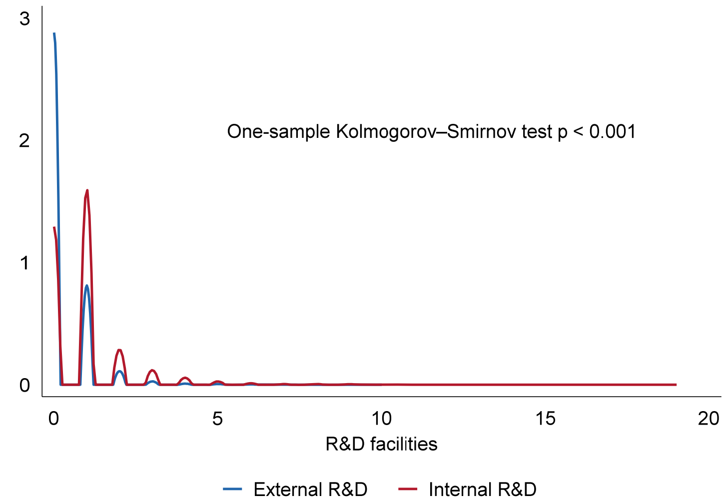


Figure 2. CAFC and R&D resources



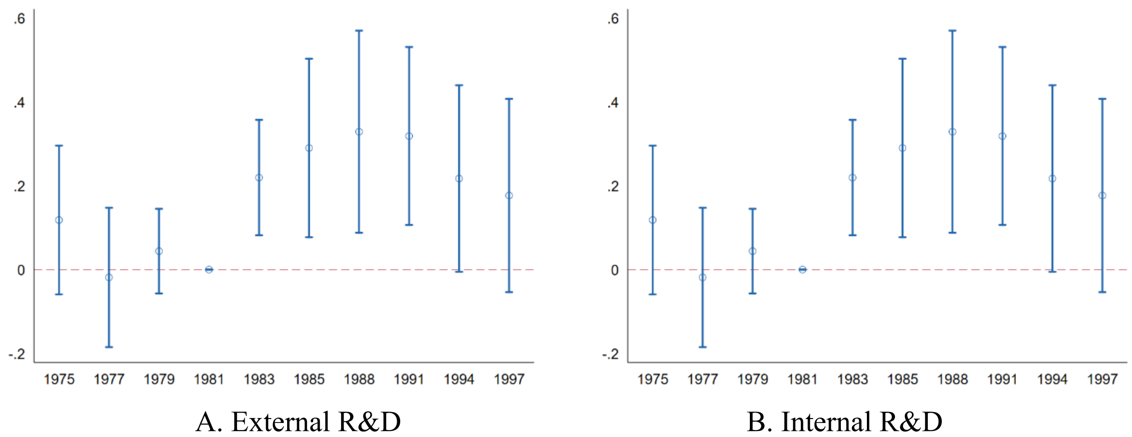
Notes: Figure graphs a binned scatter plot of the changes in the numbers of R&D facilities which performed internal and external R&D against the changes in the legal protection of patents in favor of patent owners (represented by the CAFC index).

Figure 3. External vis-à-vis internal R&D



Notes: Figure plots the kernel density distributions of external and internal R&D. By a one-sample Kolmogorov-Smirnov test, the null hypothesis that the two empirical distributions are identical is rejected ($p < 0.001$).

Figure 4. CAFC and R&D resources: Event studies



Notes: Figure plots coefficients of CAFC (and 95 percent confidence intervals) of estimates of the numbers of facilities that performed external and internal R&D in which the increase in the legal protection of patents due to the CAFC is hypothetically stipulated to take place in the year noted on the horizontal axis. The year 1981 is excluded as the reference.

Table 1. Summary statistics

	Unit	Pre-CAFC N	Pre-CAFC Mean	Post-CAFC N	Post-CAFC Mean
Panel A. Company-Circuit-Year					
Facilities		4391	1.08	6113	1.00
Facilities on internal R&D		4391	1.03	6113	0.88
Facilities on external R&D		4391	0.34	6113	0.31
p (External < Internal)			< 0.001		< 0.001
Panel B. Company-Year					
Employees		1791	13443.67	3222	7101.61
Revenue per employee	$million	1791	0.07	3222	0.17
PPE per employee	$million	1791	0.03	3222	0.09
EBITDA per employee	$million	1791	0.01	3222	0.01
R&D expenditure	$million	1791	15.64	3222	39.40
Number of companies		1791	462.0	3222	821.2

Notes: Sample: Compustat companies. Unit of analysis: Panel A: Company-circuit-year; Panel B: Company-year. Number of companies is the average number in the sub-sample over the pre- and post-CAFC periods. Owing to entries and exits, the number of companies varied over time. The total number of companies that were ever included in the overall sample (pre- and post-CAFC) is 1321.

Table 2. CAFC and R&D resources

VARIABLES	(a) All facilities	(b) External R&D	(c) Internal R&D	(d) All facilities	(e) External R&D	(f) Internal R&D
CAFC	0.330***	0.497**	0.309***	0.330***	0.504**	0.308***
	(0.112)	(0.204)	(0.116)	(0.113)	(0.207)	(0.116)
Employment	0.215***	0.291***	0.209***	0.214***	0.260***	0.206***
	(0.031)	(0.055)	(0.033)	(0.035)	(0.068)	(0.037)
Revenue per employee	0.218	1.001*	0.056	0.215	0.855	0.042
	(0.283)	(0.604)	(0.295)	(0.293)	(0.637)	(0.301)
PPE per employee	-0.633*	-1.110*	-0.555	-0.635*	-1.135*	-0.556
	(0.351)	(0.634)	(0.354)	(0.350)	(0.643)	(0.353)
EBITDA per employee	-1.054**	-1.192	-1.118**	-1.052**	-1.062	-1.107**
	(0.414)	(1.380)	(0.438)	(0.420)	(1.413)	(0.442)
R&D				0.001	0.048	0.005
				(0.027)	(0.055)	(0.027)
Missing R&D				-0.006	-0.061	0.001
				(0.076)	(0.148)	(0.083)
Observations	10,504	5,215	9,958	10,504	5,215	9,958
Company-Circuit FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Companies	1321	676	1256	868	1774	1897
Chi-squared	82.16	40.86	63.39	47.72	65.85	85.09
Mean of the DV	1.05	0.33	0.99	1.05	0.33	0.99
Absolute change	0.20	0.20	0.18	0.20	0.20	0.18
Proportionate change	22.0%	35.0%	20.5%	22.0%	35.5%	20.4%
p (External vs. Internal)		0.002			0.005	

Notes: Unit of analysis: Company-circuit-year; Estimated by quasi-maximum likelihood (ppmlhdfe); All estimates control for employment (asinh), revenue per employee (asinh), PPE per employee (asinh), EBITA per employee (asinh), and fixed effects for company x circuit and year. Columns (a) and (d): Dependent variable: number of facilities; Columns (b) and (e): Dependent variable: number of facilities engaged in external R&D; Columns (c) and (f): Dependent variable: number of facilities engaged in internal R&D. Absolute change is the change in the predicted value of the outcome due to average CAFC. Proportionate change of dependent variable is calculated as exp (coefficient of CAFC x average CAFC) – 1. *p*-value for the differences in the coefficients of CAFC on external and internal is calculated from a permutation test of 1,000 repetitions. Standard errors clustered two-way by company x circuit, in parentheses (*** $p<0.01$, ** $p<0.05$, * $p<0.1$).

Table 3. Contingency: Technological diversity

VARIABLES	High tech specialization		Low tech specialization	
	(a) External	(b) Internal	(c) External	(d) Internal
CAFC	1.025***	0.294*	0.446*	0.421***
	(0.353)	(0.153)	(0.246)	(0.142)
Observations	2,343	5,127	1,788	3,440
Company-Circuit FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Companies	505	1065	260	361
Chi-squared	15.02	14.99	29.10	48.25
Economic effect	85.6%	19.4%	30.8%	28.9%
Facility change	0.50	0.17	0.22	0.30
Pre-CAFC mean	0.79	1.13	0.85	1.41
p (External vs. Internal)	0.003		0.48	
p (High vs. Low)	0.024			

Notes: Unit of analysis: Company-circuit-year; Estimated by quasi-maximum likelihood (ppmlhdfe); All estimates control for employment (asinh), revenue per employee (asinh), PPE per employee (asinh), EBITA per employee (asinh), and fixed effects for company x circuit and year. Dependent variable: Columns (a) and (c): Dependent variable: number of facilities on external R&D; Columns (b) and (d): Dependent variable: number of facilities on internal R&D. Sample split by whether technological specialization is higher/lower than the industry (3-digit SIC) median. Absolute change is the change in the predicted value of the outcome due to average CAFC. Proportionate change of dependent variable is calculated as exp (coefficient of CAFC x average CAFC) – 1. *p*-value for the differences in the coefficients of CAFC on external and internal is calculated from a permutation test of 1,000 repetitions. Standard errors clustered two-way by company x circuit, in parentheses (*** $p<0.01$, ** $p<0.05$, * $p<0.1$).

Table 4. Contingency: Patent effectiveness

	High patent effectiveness for products		Low patent effectiveness for products		High patent effectiveness for processes		Low patent effectiveness for processes	
VARIABLES	(a) External	(b) Internal	(c) External	(d) Internal	(e) External	(f) Internal	(g) External	(h) Internal
CAFC	0.352	0.307**	0.832**	0.308	0.127	0.162	0.787***	0.503**
	(0.275)	(0.143)	(0.363)	(0.200)	(0.267)	(0.132)	(0.288)	(0.203)
Company-Circuit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,527	6,988	1,688	2,970	3,030	6,065	2,185	3,893
Companies	449	845	227	411	393	755	283	501
Chi-Squared	31.00	41.82	13.35	21.53	29.84	31.85	17.20	32.15
Mean of the DV	0.33	0.99	0.33	0.99	0.33	0.99	0.33	0.99
Absolute change	0.14	0.19	0.32	0.18	0.05	0.10	0.32	0.29
Proportionate change	23.7%	20.4%	65.2%	20.4%	8.0%	10.3%	60.7%	35.4%
p (External – Internal)	0.376		0.017		0.443		0.112	
p (High – Low)	0.059				0.158			

Notes: Unit of analysis: Company-circuit-year; Estimated by quasi-maximum likelihood (ppmlhdfe); All estimates control for employment (asinh), revenue per employee (asinh), PPE per employee (asinh), EBITA per employee (asinh), and fixed effects for company x circuit and year. Columns (a), (c), (e), (g): Dependent variable: number of facilities engaged in external R&D; Columns (b), (d), (f), (h): Dependent variable: number of facilities engaged in internal R&D. Columns (a)-(d): Sample split by whether firms operating in industries with above or below median effectiveness for new products; Columns (e)-(h): Sample split by whether firms operating in industries with above or below median effectiveness for new processes. Absolute change is the change in the predicted value of the outcome due to average CAFC. Proportionate change of dependent variable is calculated as exp (coefficient of CAFC x average CAFC) – 1. *p*-value for the differences in the coefficients of CAFC on external and internal is calculated from a permutation test of 1,000 repetitions. Standard errors clustered two-way by company x circuit, in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

Appendix B. CAFC index

We use the CAFC index constructed in Hou et al. (2023b) to represent variation in the extent to which patent law was strengthened across different circuits due to the establishment of the CAFC. The index is estimated using the equation below:

$$Z_{pct} = \beta X_{pct} + \epsilon_{pct} = \sum_{c=1}^{11} \eta_c \times Circuit_c + \sum_{c=1}^{11} \lambda_c \times postCAFC_c$$

$$+\mu_c Claims_p + \mu_B Business + \mu_t TechCat_p + \mu_O OwnerDef_p + \mu_H HomeCircuit_p + \mu_A Appeal_P + \mu_t + \epsilon_{pct}$$

The variable, Z_{pct}, takes the values of 0, 1, and 2, increasing in the order of patent litigation outcomes of invalid, valid but not infringed, and valid and infringed. Hou et al. (2023b) used ordered logit to estimate the above equation and controlled for different patent and litigation characteristics and year fixed effects. For convenience, Table B1 reproduces the estimates.

Table B1. CAFC Index

	Pre-CAFC ruling in favour of patent owner	Post-CAFC ruling in favour of patent owner	CAFC index (Change in patent law)
1st Circuit	-0.42	1.38	1.80
2nd Circuit	0.28	1.27	0.99
3rd Circuit	0.00	0.77	0.77
4th Circuit	0.47	1.46	0.99
5th Circuit	1.20	1.29	0.09
6th Circuit	0.54	1.14	0.60
7th Circuit	0.72	1.10	0.39
8th Circuit	-0.07	0.72	0.79
9th Circuit	0.69	1.12	0.43
10th Circuit	1.59	1.46	-0.12
11th Circuit	1.20	1.10	-0.10
Average	0.56	1.16	0.60

Source: Hou et al. (2023b)

In a check of robustness to possible forum shopping, we use another index, weighted to account for the likelihood of litigation in other circuits (Hou et al. 2023a, Appendix C, Table C2), reproduced here for completeness.

Table B2. Weighted CAFC index

	Pre-CAFC ruling in favour of patent owner	Post-CAFC ruling in favour of patent owner	CAFC index (Change in patent law)
1st Circuit	0.39	1.27	0.88
2nd Circuit	0.45	1.16	0.71
3rd Circuit	0.55	1.03	0.48
4th Circuit	0.54	1.22	0.68
5th Circuit	1.77	1.24	-0.53
6th Circuit	0.80	1.12	0.32
7th Circuit	0.76	1.11	0.35
8th Circuit	0.64	0.90	0.26
9th Circuit	0.69	1.14	0.45
10th Circuit	1.36	1.24	-0.13
11th Circuit	1.77	1.05	-0.72
Average	0.88	1.13	0.25

Source: Hou et al. (2023a), Appendix C, Table C2.

Appendix C. Industry distribution

Table C1 lists the distribution of company-circuit-year observations across industries in our sample.

Table C1. Industry distribution

		Sample distribution		R&D facilities		
		(a)	(b)	(c)	(d)	(e)
SIC	Industry	Freq.	Percent	Total	Internal	External
20	Food and kindred products	530	5.05	0.96	0.92	0.15
21	Tobacco products	9	0.09	0.56	0.56	0.22
22	Textile mill products	174	1.66	1.17	1.11	0.13
23	Apparel and other Finished Products Made from Fabrics and Similar Materials	75	0.71	0.77	0.72	0.09
24	Lumber and Wood Products, except Furniture	40	0.38	0.93	0.93	0.18
25	Furniture and Fixtures	99	0.94	0.81	0.80	0.07
26	Paper and allied products	379	3.61	1.13	1.09	0.17
27	Printing, publishing, and allied products	34	0.32	1.00	1.00	0.26
28	Chemicals and allied products	1,812	17.25	1.08	1.01	0.28
29	Petroleum refining and related industries	241	2.29	0.85	0.82	0.19
30	Rubber and miscellaneous plastics products	309	2.94	0.86	0.83	0.19
31	Leather and leather products	42	0.4	1.00	0.95	0.33
32	Stone, clay, glass, and concrete products	252	2.4	0.99	0.96	0.24
33	Primary metal industries	430	4.09	0.77	0.73	0.25
34	Fabricated Metal Products, except Machinery and Transportation Equipment	587	5.59	0.92	0.86	0.30
35	Industrial and Commercial Machinery and Computer Equipment	1,439	13.7	1.00	0.90	0.36
36	Electronic and other Electrical Equipment and Components, except Computer Equipment	1,564	14.89	1.04	0.93	0.37
37	Transportation Equipment	966	9.2	1.30	1.12	0.56
38	Measuring, Analyzing, and Controlling Instruments; Photographic, Medical and Optical Goods; Watches and Clocks	1,391	13.24	1.07	0.93	0.42
39	Miscellaneous Manufacturing Industries	131	1.25	0.81	0.75	0.21
	Total	10,504	100	1.03	0.94	0.32

Appendix D. Measurement

As reported in the main text, we defined external R&D to include the Cattell categories of "Contract R&D for others", "contract for industry", and "Consultation for others". Still, to check sensitivity to possible misclassification, we estimated the effects of the CAFC with external R&D defined to include only "Contract for Industry" and excluding "Consultation for others".

Referring to Table D1, column (a), presents the estimate of the effect of the CAFC using the narrower definition of external R&D. The coefficient of CAFC is precisely estimated but somewhat smaller than the preferred estimate (Table 2, column (b)). Table D1, column (b), reproduces the preferred estimate of internal R&D (Table 2, column (c)). The permutation test rejects the null hypothesis that the CAFC had equal effect on external and internal R&D (p = 0.022).

Another measurement issue is the measure of resources. We reasoned that using the numbers of facilities engaged in internal and external R&D to represent the allocation of resources between the two segments produced conservative estimates of the effects of the CAFC. To examine this claim, we use the Cattell data on R&D personnel (professional and technical), which was available for almost half of the facilities.

We then aggregated the non-missing personnel information to company-circuit-year level, and estimated the following equation,

$$Y_{ict} = \beta_0 + \beta_1 \times Internal_{ict} \times CAFC_c \times Post_t + \beta_2 \times External_{ict} \times CAFC_c \times Post_t + \beta_3 \times Both_{ict} \times CAFC_c \times Post_t + X_{ct} + \eta_t + \lambda_i + \epsilon_{ict},$$

where the dependent variable, Y_{ict}, is the number of professional and technical R&D personnel employed by firm i in circuit c in year t. $Internal_{ict}$ indicates if firm i performed only internal R&D in in circuit c in year t, $External_{ict}$ indicates if firm i performed external only R&D in circuit c in year t, and $Both_{ict}$ indicates if firm i engaged in both internal and external R&D in circuit c in year t.

Table D1, columns (c)-(d), report the estimates. Referring to Table D1, column (c), the coefficient of only external R&D is largest, followed by the coefficient of both external and internal R&D, and then the coefficient of only internal R&D. Table D1, column (d), reports the test of the identifying assumption that the CAFC is not correlated with the measurement error. Firstly, the coefficients of the interactions, CAFC x internal only and CAFC x both internal and external, are not significant. Besides, the implied effect sizes are much smaller than the main effects of internal only and both internal and external. These results suggest that CAFC did not affect the R&D personnel for facilities engaged purely in internal R&D or those engaged in both internal and external R&D. This finding supports our argument that measurement error does not bias our estimates for the effect of the CAFC on internal R&D. By contrast, the coefficient of the interaction, CAFC x external only, is positive and significant. This result suggests that stronger patent protection was associated with the allocation of additional personnel resources to external R&D, and suggests that estimates using counts of facilities to represent the allocation of technological resources produce conservative findings.

Table D1. Measurement error

VARIABLES	(a) External R&D (excl consulting)	(b) Internal R&D	(c) All personnel	(d) All personnel	(e) Personnel on external R&D	(f) Personnel on internal R&D
CAFC	0.462	0.309		0.382	1.740*	0.756*
	(0.239)	(0.116)		(0.463)	(0.958)	(0.452)
Internal only			0.298***	0.301***		
			(0.064)	(0.058)		
External only			0.395***	0.166		
			(0.101)	(0.177)		
Both internal and external			0.317***	0.345***		
			(0.058)	(0.091)		
CAFC x Internal only				0.032		
				(0.077)		
CAFC x External only				0.901***		
				(0.300)		
CAFC x Both Internal and external				0.008		
				(0.112)		
Observations	4,729	9,958	9,137	6,768	1,163	4,999
Company-Circuit FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Companies	628	1256	819	764	173	581
Chi-squared	29.68	63.39	98.18	80.59	11.34	10.72
Mean of the DV	0.27	0.99			4.02	40.11
Absolute change	0.17	0.18			58.17	51.07
Proportionate change	32.2%	20.5%			185.6%	57.7%
p (External versus Internal)	0.022				0.007	

Notes: Unit of analysis: Company-circuit-year; Estimated by quasi-maximum likelihood (ppmlhdfe); All estimates control for employment (asinh), revenue per employee (asinh), PPE per employee (asinh), EBITA per employee (asinh), and fixed effects for company x circuit and year. Column (a): Dependent variable: number of facilities engaged in external R&D excluding consulting for others; Column (b): Dependent variable: number of facilities engaged in internal R&D; Columns (c) and (d): Dependent variable: number of R&D personnel; Column (e): R&D personnel engaged in external R&D; Column (f): Dependent variable is R&D personnel engaged in internal R&D. Absolute change is the change in the predicted value of the outcome due to average CAFC. Proportionate change of dependent variable is calculated as exp (coefficient of CAFC x average CAFC) – 1. *p* value for the differences in the coefficients of CAFC on external and internal is calculated based on a permutation test of 1,000 permutations. Standard errors clustered two-way by company x circuit, in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

As a robustness check, we re-estimated equation (1) with technological resources represented by the number of R&D personnel rather than count of facilities. For facilities engaged in both internal and external R&D, we apportion the personnel by the ratio of personnel in facilities engaged only in internal R&D relative to those engaged only in external R&D in the same circuit. (For instance, Illinois Tool Works Inc., in the 7th circuit in 1994, employed 162 R&D personnel in pure internal R&D facilities, 100 in pure external R&D facilities, and 19 people in facilities that engaged in both internal and external R&D. Then, we apportioned 61.8

percent (= 162/(100+162)) of the 19 to internal R&D and 38.1 percent (= 100/(100+162)) to external R&D.)

Referring to Table D1, columns (e) and (f), the effect of CAFC on external R&D is positive and significantly larger than that on internal R&D (p=0.007). Moreover, these estimates confirm that the findings based on the main estimates using facility counts (Table 2) are indeed conservative: Table D1, columns (e)-(f), imply that the CAFC, on average, increased resources on external R&D by 185.6 percent and internal R&D by 57.7 percent. These are larger than the preferred estimates (Table 2) which implied a 35.0 percent increase in external R&D and 20.5 percent increase in internal R&D.

Appendix E. Validation

Here, we report several validation exercises which support the empirical finding that stronger patent protection raised the marginal return from external R&D relatively more than internal R&D.

In one validation exercise, we consider the effect of CAFC on R&D for the government. Similar to contract R&D for external clients, firms engage in R&D for the government, which produces technology that can possibly be commercialized. At baseline, businesses allocated less resources to government R&D than internal R&D. Our theory predicts that the effect of CAFC on government R&D would not differ from that on external R&D, but would exceed that internal R&D. Referring to Table E1, column (a), the coefficient of CAFC on government R&D is 0.628, with implied economic effect being 46.1%. Consistent with the theory, a permutation test does not reject the null hypothesis that the coefficient of CAFC on government R&D is equal to the coefficient of CAFC on external R&D (Table 2, column (b)) ($p < 0.135$), and a permutation test does reject the null hypothesis the coefficient of CAFC on government R&D is equal to the coefficient of CAFC on internal R&D (Table 2, column (c)) ($p < 0.001$).

Table E1. Validation exercises

VARIABLES	Company-circuit-year	Company-year	
	(a) Government R&D	(b) External R&D	(c) Internal R&D
CAFC	0.628	0.328	0.112
	(0.722)	(0.218)	(0.135)
Observations	1,462	2,991	4,811
Company-circuit FE	Yes	n.a.	n.a.
Company FE	n.a.	Yes	Yes
Year FE	Yes	Yes	Yes
Companies	256	674	1253
Chi-squared	7.57	33.34	34.14
Mean of the DV	0.16	0.81	2.43
Absolute change	0.22	0.22	0.14
Proportionate change	46.1%	21.9%	7.0%
p (External vs Government)	0.135		
p (Internal vs Government)	< 0.001		
p (External vs Internal)		0.025	

Notes: All columns are estimated by estimated by Poisson Quasi-Maximum Likelihood (Correia et al. 2020), and control for employment (ln), revenue per employee (asinh), PPE per employee (asinh), company-circuit fixed effects and year fixed effects. Column (a): Unit of analysis is company-circuit-year; Dependent variable: number of facilities engaged in government R&D; Columns (b) and (c): Unit of analysis is company-year. Column (b): Dependent variable: number of facilities engaged in external R&D; Columns (c): Dependent variable: number of facilities engaged in internal R&D. Absolute change is the change in the predicted value of the outcome due to average CAFC. Proportionate change of dependent variable is calculated as exp (coefficient of CAFC x average CAFC) – 1. *p* value for the differences in the coefficients of CAFC on external and internal is calculated based on a permutation test of 1,000 permutations. Standard errors clustered two-way by company x circuit, in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

Table E1, columns (b) and (c), report estimates to examine our assumption that companies decentralized the allocation of resources to the circuit level. To investigate, we stipulate the alternative: that companies allocated resources at corporate headquarters. We compile a company-year panel of technological resources aggregated to the parent company level and match technological resources with the CAFC index at the headquarter circuit. The coefficients of the CAFC index in external and internal R&D are respectively about one-third and two-thirds smaller than the preferred estimates (Table 2, columns (b) and (c)). The attenuation of the coefficients is consistent with measurement error. We interpret the result as validating our assumption of decentralized allocation of resources. Yet, despite the measurement error, these estimates also show that stronger patent protection increased external R&D more than internal R&D ($p = 0.025$).

Appendix F. Forum shopping

Here, we report supplementary estimates to check the sensitivity of our findings to the home circuit assumption, which would be violated by forum shopping in patent litigation.

Table F1, column (a), reports an estimate with the original CAFC index replaced by a weighted CAFC index that considers the likelihood of companies in one circuit litigating in another circuit (Table B2 above). The coefficient of CAFC on external R&D, 0.672, exceeds that of CAFC on internal R&D, 0.573. A permutation test yields $p = 0.135$.

Table F1. Forum shopping

VARIABLES	(a) Weighted CAFC index (Hou and Png 2023a)	(b) Infringer in home circuit	(c) Infringer in another circuit	(d) Exclude 3rd, 8th, 11th Circuits	(e) Years up to 1990
CAFC on external	0.672	0.414	0.568	0.473	0.487
CAFC on internal	0.573	0.248	0.362	0.304	0.342
p (External versus Internal)	0.135	0.017	0.003	0.014	0.098

Notes: Unit of analysis: Company-circuit-year; Columns (a)-(d): Dependent variable: number of facilities performing external R&D, estimated by Poisson Quasi-Maximum Likelihood (Correia et al. 2020). The table only presents the coefficients for CAFC index. All estimates control for employment (ln), revenue per employee (asinh), PPE per employee (asinh), company x circuit fixed effects and year fixed effects. Columns (a): CAFC is the weighted CAFC index (Hou et al. 2023a) presented in Table B2 above; Column (b): CAFC is decomposed to CAFC index multiplied by the likelihood of home circuit (reported before the slash) and CAFC index multiplied by the likelihood of forum shopping (reported after slash); Column (c): Sample excludes the 3rd, 8th and 11th circuits; Column (d): Limiting sample period to 1990 and earlier. Standard errors bootstrapped and clustered two-way by company x circuit.

In another robustness check, we explicitly consider the likelihood of forum shopping at the company level. Until October 1990, patent cases were required to be filed in the location of the defendant: "Any civil action for patent infringement may be brought in the judicial district where the defendant resides, or where the defendant has committed acts of infringement and has a regular and established place of business" (28 USC §100(b)). Thus, businesses could only shop for a forum to the extent that those which infringed their patents were located in circuits outside their home circuit.

We stipulate the likelihood of forum shopping being the proportion of competitors (defined as businesses that patented in the same dominant technological class as the subject firm) located outside the home circuit of the subject firm. Then, we construct two CAFC indexes: the CAFC index multiplied by the likelihood of litigation in the home circuit (home circuit CAFC index) and the CAFC index multiplied by the likelihood of forum shopping (forum shopping CAFC index). Table F1, columns (b) and (c), present the estimates applying the two indexes. For both internal and external R&D, the effect of the CAFC index is positive regardless of whether competitors were located in the home circuit or elsewhere. In both cases, the permutation test rejected the null hypothesis that the effect of the CAFC was the same on external and internal R&D.

Finally, Table F1, columns (d) and (e), report two additional checks of robustness to forum shopping. One excludes the 3rd, 8th, and 11th circuits, in which the CAFC shifted the interpretation of the law in favor of patent owners to the largest extent and where forum shopping would have had the largest impact. The other robustness check limits the sample to the years up to 1990, before a key CAFC decision relaxed rules on forum shopping (Chien and Risch 2017).

Appendix G. Alternative explanations

An alternative explanation is that the CAFC reduced the risk to the technology firm of its proprietary knowledge being misappropriated in the course of performing external R&D, and so, increased engagement in external R&D.

One test of this argument is presented in Table 4, in which we show that while patent effectiveness for new products significantly amplifies the effect of patent protection on external relative to internal R&D, patent effectiveness for new processes does not significantly predict the difference. The contrast supports our theory in patent protection increases appropriability for future returns of new technologies in which products might matter more, and nullify the argument of misappropriation risk in external R&D in which tacit knowledge about processes are more important.

Alternatively, Table G1, columns (a) and (d), contrast the effects of CAFC on external vis-à-vis internal R&D in firms located in circuits with high/low misappropriation risk (as represented by the percent of R&D facilities in the circuit owned by other firms in the same 3-digit SIC industry). The difference in the effect of stronger patent protection on external relative to internal R&D is only marginally significant between firms subject to high vis-à-vis low misappropriation risk ($p = 0.1$). Taken together, we conclude that the evidence for the misappropriation mechanism is weaker than for our preferred interpretation.

Another alternative explanation is that the CAFC addressed potential hold-up in the delivery of external R&D services, which then increased the demand for external R&D. To test this channel, Table G1, columns (e)-(h), show that inconsistent with the hold-up story, the pre-CAFC level of external R&D engagement does not moderate the differences in how patent protection affected external relative to internal R&D.

Table G1. Alternative explanation

	High misappropriation risk		Low misappropriation risk		High external R&D pre-CAFC		Low external R&D pre-CAFC	
VARIABLES	(a) External	(b) Internal	(c) External	(d) Internal	(e) External	(f) Internal	(g) External	(h) Internal
CAFC	0.650	0.224	0.378*	0.388***	0.522*	0.534**	0.172	0.122
	(0.447)	(0.273)	(0.225)	(0.127)	(0.281)	(0.209)	(0.332)	(0.114)
Observations	1,319	2,253	3,490	7,091	2,206	3,050	1,934	4,189
Company-circuit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Companies	271	500	517	983	227	213	152	333
Chi-squared	12.25	13.01	34.73	52.12	12.74	18.68	15.08	38.18
Economic effect	48.0%	14.5%	25.6%	26.4%	37.0%	38.0%	10.9%	7.7%
Facility change	0.35	0.22	0.14	0.19	0.26	0.38	0.05	0.07
Pre-CAFC mean	0.88	1.79	0.58	0.86	0.90	1.22	0.28	0.95
p (External versus Internal)	0.08		0.487		0.47		0.411	
p (High versus Low)	0.1				0.418			

Notes: Unit of analysis: Company-circuit-year; All columns are estimated by estimated by Poisson Quasi-Maximum Likelihood (Correia et al. 2020), and control for employment (ln), revenue per employee (asinh), PPE per employee (asinh), company-circuit fixed effects and year fixed effects. Columns (a), (c), (e) and (g): Dependent variable: number of facilities engaged in external R&D; Columns (b), (d), (f) and (h): Dependent variable: number of facilities engaged in internal R&D. Columns (a)-(d): Split the sample by whether misappropriation risk of the firm is higher than the industry (3-digit SIC) median. Columns (e)-(h): Split the sample by whether firms engaged in above or below industry (3-digit SIC) median level of external R&D in the pre-CAFC era. Absolute change is the change in the predicted value of the outcome due to average CAFC. Proportionate change of dependent variable is calculated as exp (coefficient of CAFC x average CAFC) – 1. *p* value for the differences in the coefficients of CAFC on external and internal is calculated based on a permutation test of 1,000 permutations. Standard errors clustered two-way by company x circuit, in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

Appendix H

Table H1 reports the results of a search of the U.S. Securities and Exchange Commission archive for R&D contracts (Google search “R&D contract site: sec.gov”) in December 12-19, 2022. The first 49 results were downloaded.

Table H1. R&D contracts

	Number
Original	49
Excluding those which did not govern R&D at all (for instance, mentioning R&D in facilities lease or loan agreement) or involved non-commercial entities such as a research institute	43
Collaborative R&D (both parties engaged in R&D)	33
Contract R&D (only one party engaged in R&D)	16
-- Client to own 100 percent of the resulting technology	11
-- Client and R&D provider to jointly own the resulting technology	5