PROFITING FROM ENABLING TECHNOLOGIES?

Alfonso Gambardella
Department of Management & Technology and ICRIOS Bocconi University, CEPR London
Università Bocconi
Via Roentgen, 1
20136 Milan, Italy
Ph: 0039-02-58363712
Fax. 0039-02-58363791
alfonso.gambardella@unibocconi.it

Sohvi Heaton,
College of Business
Loyola Marymount University
Sohvi.heaton@lmu.edu

*Elena Novelli**
The Business School (formerly Cass)
City, University of London
106 Bunhill Row
London EC1Y 8TZ UK
Ph: 0044-(0)20-7040-0991
Fax: 0044-(0)20-7040-8328
novelli@city.ac.uk

David Teece,
Institute for Business Innovation, Haas School of Business,
University of California, Berkeley
teece@haas.berkeley.edu

* Corresponding author

Keywords: Profiting from Innovation, Enabling Technologies, General Purpose Technologies, Appropriability

Acknowledgements: Authors names are in alphabetical order. The authors would like to thank Jonathan Barnett, Wes Cohen, Raffaele Conti, the participants of the AOM Symposium "Strategic management of emerging technologies" at the Academy of Management Annual Meeting 2018 and the participants of the AOM Symposium "The interplay of firm strategy and industry lifecycle" at the Academy of Management Annual Meeting 2020

PROFITING FROM ENABLING TECHNOLOGIES?

Abstract

How to profit from innovation has been an important question for both innovation scholars and practitioners over the years. It is certainly a relevant question for all types of technological innovation, including emerging ones. Teece's (1986) profiting from innovation (PFI) framework sets forth a theory of the relevant contingencies. However, Teece's framework focuses on technologies with applications in specific domains. We focus on the question of how to *profit from enabling technologies*: technologies that are applicable across multiple domains. We argue that capturing value in such circumstances is fundamentally different from profiting from less-enabling technologies and raises new issues with respect to the relevant business models and public policies. This paper's contribution is threefold. It formally revises and extends the original PFI framework to include the case of enabling technologies; it provides empirical evidence to support the distinction between profiting from enabling as compared to profiting from narrower "discrete" technologies; and it generates perspectives on the appropriate business models for these technologies and discusses related public-policy implications, in light of the fact that the share of the benefits the innovator can capture is likely to be even smaller for enabling than for discrete technologies.

I. Introduction

How to profit from innovation remains an important question for innovation scholars, practitioners, and policymakers. It is a relevant question for all types of technological innovation, including emerging ones. A touchstone for research in this context is the seminal work by Teece (1986, 2006, 2018a, 2018b), who develops a comprehensive theory of the factors that impact the division of the gains from innovation. Teece focuses on a key question: under what conditions should an innovator sell or license its invention to producers of goods and services, as opposed to becoming a producer of goods or services himself or herself (i.e., integrating the innovation into a product or a service for the final customer)? Teece's profiting from innovation (PFI) framework has guided academics and practitioners in understanding the problem for more than thirty years. It has also informed public policy by emphasizing that capturing value from innovation depends on not just intellectual property, but also the availability and ownership of complementary assets and complementary technologies, supporting the evolution of standards, and getting timing right (Teece, 1986, 2006).

In this paper, we suggest that crucial aspects of the appropriability problem are not captured adequately by the PFI 1986 framework. One feature of Teece's initial framework is its clearly articulated applicability to a "discrete" invention with narrow downstream applicability: "a new product design concept" (Teece, 1986, p.291). Here, we suggest that at least one important category of technology (i.e., enabling technologies) will not fit comfortably in the framework and requires further analysis and modifications to the framework. Enabling technologies are upgradable, adaptable technologies with improvement potential that have broad applicability (see Rosenberg, 1963; Bresnahan & Trajtenberg, 1995; Bresnahan & Gambardella, 1998; Teece, 2018a; Conti et al., 2019a). Enabling technologies are found in many contexts, ranging from computer science algorithms to lasers to chemicals. For example, some artificial intelligence algorithms are specifically targeted to an application; others, more general or enabling, can be used in genetics, robotics, or natural language applications. Similarly, some types of lasers can be used only in specific applications such as dermatology; the more enabling lasers, instead, have broader applicability across diverse settings such as dermatology, industrial machinery, and military.

We argue that understanding how firms can profit from enabling technologies is important because of emerging management and policy issues associated with breakthrough enabling technologies, such as blockchain, artificial intelligence, and 5G wireless communication, which are likely to have massive impacts on business and society. Profiting from enabling technologies is fundamentally different from profiting from more narrowly applicable ones (see also Teece, 2018a, 2018b, 2018c).

From a private perspective, recognizing the specialized challenges of profiting from enabling technologies leads to the identification of the business models that may allow the inventor of an enabling technology to capture value from it (Leih & Teece, 2017; Teece, 2018a, 2018b, 2018c). This is crucial for the design of a policy system that can ensure that this type of innovation is encouraged (Arrow, 1962; Levin et al., 1987; Cohen et al., 2000; Winter, 2006; Schumpeter, 1950).

This paper's contribution is threefold. First, it contextualizes the problem of profiting from innovation for the case of enabling technologies (section II). Second, using the Patval survey of inventors (Torrisi et al., 2016; Hoisl & Mariani, 2016) in combination with other datasets, it provides empirical evidence on the distinction between discrete and enabling technologies when profiting from innovation (section III). Third, it systematically revises and extends the original PFI framework with particular consideration of enabling technologies (section IV). Finally, it offers reflections for strategic management researchers and practitioners as well as policymakers regarding profiting from enabling technologies (section V).

II. Extending the Profiting from Innovation Framework to Enabling Technologies

Teece's seminal 1986 article focused on an important question: how should the configuration of strategic and organizational activities of innovators—including the innovators' business models—be designed to increase the chance that the innovators themselves (rather than imitators and other followers) appropriate returns from their R&D investments? Teece (1986) developed what has become known as the profiting from innovation (PFI) framework, a simple and elegant conceptual model that identified the contingencies for profiting from innovation in different settings. It represented a turning point compared to the industrial organization and technology management approaches that preceded it. It brought attention to the fact that, despite policymakers' efforts to create mechanisms to assist innovators, history is replete with examples of innovators who have never been able to appropriate the economic returns from their innovations, and imitators who achieved commercial success ahead—if not instead—of the innovators.

In this paper, we emphasize that the PFI theory requires further elucidation to be able to embrace the idiosyncratic characteristics of enabling technologies. Enabling technologies are both expandable and adaptable technologies (Teece, 2018a, 2018b, 2018c; see also Conti et al., 2019a and b, who refer to them as to "general technologies"). They are more general than "discrete" (narrowly applicable) technologies and can impact multiple market segments. Examples of enabling technologies are available in today's economy. For instance, artificial intelligence algorithms can be applied to a wide variety of contexts (e.g., to understand speech, recognize faces, and drive vehicles). In mobile telecoms, 3G and 4G technology might be thought of as enabling technologies, with mobility for applications such as Facebook, location-sensitive mapping, and streaming media (Teece, 2018a, p.1369).

The concept of enabling technologies builds on the related concept of general purpose technologies (Bresnahan & Trajtenberg, 1995; Bresnahan & Gambardella, 1998). Enabling technologies can be thought of as "junior GPTs" in that they share with GPTs the characteristic of being applicable across domains, but their breadth of application is not necessarily so high that it has a measurable impact on the economic growth of the entire economy.[1]

Superficially, the broad applicability of enabling technologies suggests that these technologies offer more opportunities for various parties to capture returns (i.e., they generate more value and profits for various institutions than do discrete technologies). However, their very breadth of applicability makes even partial value appropriation by the innovator difficult (see also Teece, 2018a, 2018b, 2018c). Put

[1] The degree of "applicability" that characterizes enabling technologies can be thought of as a varying on a continuum (Conti et al., 2019a and b). In this work, for simplicity, we focus on the two extremes of this spectrum and compare and contrast the case of very general and broadly applicable "enabling technologies" with the case of narrowly applicable "discrete" technologies.

differently, while the opportunity for value capture may be high because of the tremendous value generated, the innovators' ability to capture a fair share of the value generated is even more limited than for discrete technologies, raising both managerial challenges and public-policy issues.

It is important to understand the nature of the value appropriation challenge associated with enabling technologies. Compared to a discrete technology, a more general technology like an enabling technology leads an innovator to face two critical tradeoffs (Conti et al., 2019a). The first is what we call the "design cost/applicability tradeoff," concerning the fact that an enabling technology might require additional design work for its development and fine-tuning across settings, increasing the overall costs faced by the innovator (Bresnahan & Gambardella, 1998; Teece, 2018a, 2018b). This implies a tradeoff between enjoying the economies of scope that broader applicability enables and incurring the extra costs for designing the technology so that it is more applicable in the first place.

A second, related, and critical tradeoff is what we call the "value/applicability tradeoff." A more enabling technology is adaptable to a larger number of markets, but that higher applicability comes at the cost of it being tuned less perfectly to each individual market (e.g., Montgomery & Wernerfelt, 1988; Bresnahan & Gambardella, 1998). For instance, lasers that have applicability for industrial drilling and dermatology tend to be less fine-tuned to either of these two settings than other lasers that are applicable only in dermatology. As the value generated for the end user is typically associated with its willingness to pay, this has an impact on the profitability of enabling technologies. It is worth noting that these two tradeoffs could be intertwined. Lower design costs in some cases might be associated with lower value across settings; and the willingness to improve the fit of the technology across different settings could lead to higher design costs. This could also depend on the other characteristics of the technology. For instance, a more complex technology (i.e. a technology composed of many interdependent components) might require much higher design costs so that the fit across different settings could be improved, which would have an impact on the economics of profiting from it.

Overall, these two tradeoffs make quite different the economics of profiting from enabling versus discrete technologies. Revising the original PFI framework to adapt it to the case of enabling technologies is, therefore, important. The original PFI framework focused on three core factors that determined the innovator's response to the profiting from innovation problem: the existence of a dominant design, the strength of the appropriability regime, and the availability of complementary assets. We note that the emergence of a dominant design, and the possible associated agreement on dominant standards, might be problematic in the case of enabling technologies. This is because the emergence of a dominant design may require coordination of players upstream and downstream across multiple markets, which tends to be difficult for enabling technologies (Bresnahan & Trajtenberg, 1995). When vertical integration is absent, the technology innovator and independent downstream parties might end up investing "too little, too late," limiting the effectiveness with which the design of the enabling technology can be successfully developed (Bresnahan & Trajtenberg, 1995, p.83). However, in this paper, we will focus our analysis on the strength of the appropriability regime and the availability of complementary assets as the two key factors that distinguish profiting from enabling and discrete technologies.

The PFI framework suggests that the appropriability regime (i.e., environmental factors that govern an innovator's ability to capture the profits generated by an innovation, such as the nature of the technology and efficacy of legal mechanisms of protection) plays a key role in determining the ability of innovators to profit from innovation. At first glance, one might conclude that the role of the strength of the appropriability regime would not change between enabling or discrete technologies, as it is mostly associated with the intrinsic characteristics of the technology and not dependent on the number of its applications. For instance, it could be argued that a chemical compound could be successfully protected by a strong patent, and that it would not matter whether that compound could be used only as a drug or whether it could be used in three different applications (for instance as a pharmaceutical compound, a chemical reagent, and an agricultural compound), as patent protection would be equally effective (or ineffective) across domains.

However, closer examination suggests that the actual strength of the appropriability regime might differ across domains where the technology is applicable. For instance, imagine an inventor operating in a strong appropriability regime and applying for a patent to protect an enabling technology. Theoretically, the inventor's patent document should be written in a way so that the patent's claims cover all the possible applications of the invention across domains. But this would be true only under the assumption that all the possible applications of the inventions are known (or could be identified easily by) the inventor at the time of the patent application (i.e., Merges & Nelson, 1990, 1994; Novelli, 2015). This is unlikely to happen because there is high uncertainty regarding the application domains at the time in which enabling technologies emerge (Rosenberg, 1998).

In practice, the extent of protection that the patent will give to the inventor depends on the inventor's ability to identify early on as many applications of the invention as possible and have those applications covered by the patent claims so that they are all protected effectively (Novelli, 2015). Doing so requires complementary technical and commercial knowledge across all the domains of application, which the inventor and retained patent attorneys might lack. Also, the extent of protection will be dependent ultimately on the innovator's ability to monitor potential infringers closely and pursue them legally; but this is difficult when the patent holder's attention needs to be spread across all domains in which the enabling technology could be applied (e.g., Merges & Nelson, 1994; Chang, 1995; Novelli, 2015). It follows that—even when operating under a strong appropriability regime—innovators who have developed an enabling technology might not be able to capitalize on the invention fully.[2]

The case of weak appropriability regime is worth reflecting upon. One way to compensate for a weak appropriability regime in Teece (1986) is for innovators to possess (or have competitive access to) the complementary assets and technologies that need to be combined with the innovation to bring it to the market. The PFI framework, therefore, ties successful value appropriation to the ownership of complementary assets and technologies, except where intellectual property rights are strong, implying a kind of substitution effect between the strength of the appropriability regime and the possession of complementary assets and technologies.

[2] In line with this argument, Novelli (2015) finds that firms with patents whose claims span across multiple technological classes (possibly associated with a more enabling technology) tend to be associated with a lower ability of the inventor to appropriate value from their invention compared to other firms (as measured by the proportion of self-forward citations to total forward citations received by the patent).

But in the case of an enabling technology, this precept must apply across multiple application areas. The challenge for the owner of the enabling technology is that complementary assets are often slow to build or expensive to acquire, and the diversity and amount of assets required to market a technology across different sectors constitutes a substantial barrier to the appropriation of returns for the owners of the technology (Conti et al., 2019a, 2019b).

Few innovators ever end up being in the actual position to appropriate value from the enabling technology via downstream entry in just one application sector (Teece, 1986), let alone all application sectors.[3] A key example of an innovator with an enabling technology is Echelon, a Silicon Valley startup company that in 1990 launched LonWorks, a networking technology that offered a universal technological solution in the context of automation systems. Although every automation system is essentially based on three components (sensor, controller, and actuator), the main applications of automations were characterized historically by industry-specific technical paradigms and know-how (Thoma, 2008). The solution advanced by Echelon was more generally applicable and could address automation across different industries. The company's initial business model targeted every automation system market at that time, including buildings, process industries, manufacturing, home automation, transportations, and utilities (Thoma, 2008). But Echelon lacked the required set of complementary assets across sectors. While tens of millions of devices in a variety of industries use LonWorks standards, Echelon struggled to capture more of the value it created and was acquired by another company for $45 million in 2018 (Echelon Corporation, 2018).

III. Profiting from Enabling Technologies: Illustrative Evidence

We provide empirical evidence in support of the arguments presented, as the limited availability of cross-industry data on firms' commercialization strategies makes it difficult to test our arguments fully. A key

[3] Nelson (1959) came close to articulating this point. He saw the scope of the business assets held by the firm as important to value capture because of uncertainty as to where the fruits of basic science would likely fall. What is true for basic research is also somewhat true for enabling technologies.

point that we illustrate empirically is that "discrete" and enabling technologies display different patterns and associations among the variables of the PFI framework. When the technology is discrete, the pattern we observe reproduces the classical profiting from innovation prediction. However, for the case of enabling technologies, the outcome is more varied.

Data

Combining data from multiple sources, we created a comprehensive and representative dataset at the invention level, in line with the PFI framework. We started from the Patval survey of inventors (Torrisi et al., 2016; Hoisl & Mariani 2016), which collects unique information on the characteristics of the inventors and their inventions and whether they were used in-house or commercialized. The Patval survey has been assembled by contacting and surveying inventors in Europe, using a harmonized questionnaire, across surveyed regions. The sample was drawn at the level of patent applications with priority dates between 2003 and 2005.[4] For each European patent listed in the survey, we selected those that had a US patent equivalent using the European Patent Office Patstat database. We combined these data with data from the Patstat, the US Patent Office PatentsView datasets, and industry-level (from the Carnegie Mellon Survey, Cohen et al., 2000)[5] and country-level data on the quality of national legal systems (Fraser Institute Index[6]).

Methodology and variables' operationalization

The purpose of our analysis was, first, to show evidence of the associations among variables discussed in the PFI framework in our full sample of patents; and, second, to show how those patterns differed for enabling and discrete technologies.

[4] 2003 was used as a lower bound of the priority years to avoid too much overlap with two inventor surveys conducted in the US and Japan (which used priority years between 1995 and 2003). 2005 was chosen as an upper bound, since Patent Cooperation Treaty (PCT) filings only enter the regional phase thirty months following the priority date. Choosing patent applications with later priority years would have led to biases due to "missing" PCT filings. After sampling the patents, one inventor listed on the patent document was chosen at random to respond to the survey.
[5] We thank Wes Cohen for providing access to these data.
[6] Available at www.fraserinstitute.org

We used two variables to identify firm's commercialization choices. This is because, in line with the PFI framework, we identified two main (non-mutually exclusive) ways to commercialize the technology: commercialization via contract (i.e., licensing or patent sale) and integration of the technology into products (see also Conti et al., 2019a). In line with this logic, we modelled the firm's choice using a Bivariate Probit model to predict the probabilities that the inventor of a focal patent would choose to profit from the invention via (1) contracting (i.e., by selling or licensing the technology) and/or (2) integration, as a function of (i) the strength of the appropriability regime in the inventor's focal industry; (ii) the inventor's access to complementary assets; (iii) interaction between the strength of the appropriability regime in the focal industry and the inventor's access to complementary assets;[7] and (iv) whether the design underlying the patent had reached the paradigmatic phase and a set of controls. Table 1 presents variable operationalization and Table 2 summary statistics and pairwise correlations among variables.

-----Insert Tables 1 and 2 about here-----

Results

Table 3 reports the results of the Bivariate Probit model. Models 1 and 2 report the results on the full sample of 7,290 inventions. They are in line with the predictions of the PFI framework: the strength of the legal appropriability regime was associated with the commercialization choice; in particular, consistent with the predictions of PFI, a stronger legal appropriability regime was associated with more technology contracting (β=0.035, p-value<0.01) and less integration (β=-0.018, p-value<0.01). The effect of the interaction between the availability of complementary assets and the strength of the appropriability regime is negative on contracting (β=- 0.068, p-value<0.01), in line with Teece's (1986) suggestion that when the appropriability regime is weak, access to complementary assets still can offer a way to profit from the technology via integration and protect the inventors against imitation.

[7] The interaction term was included in the contracting equation only, in line with the intuition that availability of complementary assets makes contracting less likely even if appropriability is high, but that this dynamic is less relevant in the case of integration. Results (available upon request) are similar when the interaction term is included in both equations, but the interaction term is not statistically significant.

-----Insert Table 3 about here-----

Results also report that the availability of complementary assets is positively associated with both contracting and integration of the technology (β=0.891, p-value<0.01; β=0.436, p-value<0.01, respectively). The positive association between the availability of complementary assets and commercialization via integration is straightforward. In our view, the positive association between the availability of complementary assets and commercialization via contracting is consistent with prior research that suggests that downstream capabilities support the upstream provider of a technology in negotiations with downstream buyers (Arora et al., 2001). Finally, results report that the technology being based on existing standards (i.e., paradigmatic phase) does not have a statistically significant impact on the contracting, but it is positively associated with integration (β=0.304, p-value<0.01). This may be related to the fact that product commercialization is likely when standards are in place already.

We then split the sample into the enabling and discrete technology patent subsamples. If we look at the subsample of discrete technologies (Models 3 and 4 in Table 3), the association between the strength of the appropriability regime and the commercialization choice shows a pattern similar to the one identified in the full sample (β=0.050, p-value<0.01 on contracting and β=-0.024, p-value<0.01 on integration). However, when we move to the sample of enabling technologies (Models 5 and 6 in Table 3), the association between the strength of the appropriability regime and the commercialization choice varied, becoming statistically nonsignificant. Higher appropriability still makes contracting more likely, but the association is smaller and the standard error of the estimate is larger.

Although these results do not represent a full test of our theory, they suggest that the strength of the appropriability regime is not clearly associated with the choice that the innovator of an enabling technology will make. When the strength of appropriability is high, innovators of an enabling technology do not take as much advantage compared to innovators endowed with a discrete technology, as the lack of the complementary knowhow and monitoring ability, and uncertainty over application, makes it difficult to use intellectual property effectively. When appropriability is weak, integration is less of a straightforward option, because it is unlikely that any innovator can integrate across the broad set of application sectors to which an enabling technology gives access. In line with this, we find also that the interaction effect between the availability of complementary assets and the strength of the appropriability regime is less statistically significant for the innovator of an enabling technology (β=- 0.067, p-value<0.05). However, when we look at the availability of complementary assets, we do not see different patterns of results between enabling and discrete technologies. This is likely related to the fact that our measure might not be completely independent from whether the technology is enabling or discrete. This is unfortunately a limitation of our data. If an ideal measure were available, we would expect to see a pattern similar to the one that we find in the case of the appropriability regime. Finally, the fact that the technology is based on standards is not statistically significant in its association with contracting, but it is significant in its association with the choice of integrating, with a stronger effect in the case of enabling versus discrete technologies (β=0.426, p-value<0.01 and β=0.217, p-value<0.01).

The average marginal effects, reported in Table 4, can offer a more precise understanding of the magnitude of the associations we observe and the comparison between discrete and enabling technologies. Results from the sample of discrete technologies (columns 3 and 4) show that—when complementary assets are not available—an increase of one standard deviation in the strength of the appropriability regime (2.337) is associated with an increase in the probability of contracting of about 1.9 percentage points and with a decrease in the probability of integrating of about 2.1 percentage points. However, there is no statistically significant effect observed in the sample of enabling technologies (columns 5 and 6).

-----Insert Table 4 about here-----

When complementary assets are available, the association between appropriability and contracting is not significant in the sample of discrete technologies. However, an increase of one standard deviation in the strength of the appropriability regime is associated with a reduction in the probability of integration by about 2.1 percentage points. In the sample enabling technologies, instead, the same increase of one standard deviation in the strength of the appropriability regime is associated with a reduction in the probability of contracting of 1.4 percentage points. Yet the strength of the appropriability regime is not associated with the probability of integrating in a statistically significant way.

Focusing on the availability of complementary assets, in the sample of *discrete* technologies, when appropriability is *low*, the availability of complementary assets is associated with an increase in the probability of contracting of about 6 percentage points and an increase in the probability of integrating of about 16 percentage points. In the sample of *enabling* technologies instead, the same condition is associated with an increase of the probability of contracting of about 8 percentage points and an increase in the probability of integrating of 17 percentage points. In the sample of *discrete* technologies, when appropriability is *high*, the availability of complementary assets is associated with a decrease in the probability of contracting of about 13 percentage points and an increase in the probability of integrating of about 15 percentage points. In the sample of *enabling* technologies instead, the same condition is associated with a decrease of the probability of contracting of about 9 percentage points and an increase in the probability of integrating of 17 percentage points. This suggests that the availability of complementary assets is not associated with a large change in the probability of integrating, depending on whether the appropriability regime is strong or not. Consistently with the results presented earlier, the substitution effect between appropriability and complementary assets is higher when appropriability is high and seems more relevant for discrete technologies than for enabling ones.

Concerning the paradigmatic phase, being in the post-dominant design period is not associated with a statistically significant change in the probability of contracting in the sample of discrete nor enabling technologies. However, it does have an effect on the probability of integration in both samples, where it is associated with an increase in probability by 8 and 16 percentage points, respectively.

IV. Business Models for Innovators of Enabling Technologies: Narrow vs. Broad Horizontal Scope in Integration and Contracting

In the previous section, we offered preliminary empirical evidence of the distinction between profiting from enabling and discrete technologies. We now focus on the business models available to innovators of these technologies. The PFI framework defined the commercialization choice along the vertical dimension. It offered innovators (and, implicitly, imitators) clear advice on the choice between (i.) contracting out (licensing out or selling) the innovation to downstream firms, which then would embed it into products and sell it in the product market versus (ii) integrating the innovation into products to be sold on the product market. It essentially provided advice on the *vertical scope* that the innovator should consider when commercializing the technology.

In considering the strategic options of an innovator with an enabling technology, it must be noted that the innovator's commercialization choice concerns not only the vertical scope of commercialization (whether to integrate or contract), but also the *horizontal* scope of commercialization. Innovators with an enabling technology *potentially* applicable across sectors must choose whether to target all or a vast portion of all possible application sectors (broad horizontal scope of commercialization); or to focus only on a few application sectors (narrow horizontal scope of commercialization). Considering this additional dimension leads to the identification of four possible strategies from which the innovator with an enabling technologies can choose: (iii) contracting with narrow horizontal scope, (iv) contracting with broad horizontal scope, (v) integration with narrow horizontal scope and (vi) integration with broad horizontal. These four additional strategies are available to innovators with an enabling technology. We graphically represent them in Figure 1, which also indicates the returns associated with each of these strategies in the relevant boxes. An innovator's returns can be represented as a function of $V_{\bullet}$, the value of the technology in each application sector (likely associated with the price that can be commanded); $r_{\bullet}$, the share of the rents that the innovator can appropriate in each application sector (with $r_{\bullet}=1$ in the case of integration) and *n,* the number of application sectors.

Reflecting on the best strategy to profit from an enabling technology implies a comparison of the returns of each of the four different strategies associated with an enabling technology (iii-vi). In the case of an enabling technology, targeting a higher *n* (broad scope of commercialization) can have a positive effect on profits (absent any cash constraints), irrespective of whether the innovator contracts out the technology or integrates it into products. In this respect, given that the innovator has an enabling technology, the choice of a broad horizontal scope (strategies iv and vi) tends to be superior to that of a narrow horizontal scope (strategies iii and v).

However, neither of these strategies is necessarily superior in terms of profits to strategies i and ii because, compared to a discrete technology, an enabling one likely creates lower value for customers in any given sector without adaptation due to the mentioned value/applicability tradeoff. In other words, it might have a decent performance in many settings, but its performance in each setting might be inferior to that of a discrete technology applicable only to (and fine-tuned for) one setting. Thus, in each individual setting, the value of the enabling technology could even be lower than the value of other available discrete ones ($V_{Ei}<V_D$). Due to the cost/applicability tradeoff, the threshold to achieve breakeven is likely higher as the innovator has likely incurred a higher cost for developing a more general enabling technology.

In addition, even under a strong appropriability regime, the share of rent that the innovator of an enabling technology obtains when contracting in settings that are further away from core areas of expertise is likely lower than that that obtained in core domains of expertise ($r_{En} < r_{En-1} <\ldots< r_{E1}$), due to the already mentioned lack of complementary skills and managerial capacity in application sectors that are further away from the innovator's core areas of expertise. Therefore, for innovators with an enabling technology, contracting with a broad scope might be associated with decreasing marginal returns. This effect could be partially compensated by the fact that a broad horizontal scope might enable the innovator of an enabling technology to extract a higher share of rents from downstream players by putting them in competition with each other ($r_{Ei}>r_D$ if $i>1$).

This discussion suggests that the actual profits accrued to an innovator will vary depending on the specific characteristics of the technology and the environment faced by the innovator that affect the actual value of the relevant parameters (e.g., actual extent of applicability of the technology, which determines n; actual strength of the appropriability regime, which determines $r_\bullet$; the complementary knowledge available to the innovator, which determines the decrease of r_{Ei} as i increases; and the reduction in value of the enabling technology compared with the alternative discrete technologies, which determines the difference between V_{Ei} and V_D) and different strategies could be appropriate.

-----Insert Figure 1 about here-----

Teece's original framework particularly emphasized how the strategic choices of the innovator and the outcome of these choices vary depending on the availability of complementary assets and the strength of the appropriability regime. We extend the original analysis in Figure 2. Three classes of participants or "players" are of interest: innovators, imitators, and owners of cospecialized assets (e.g., distributors). The vertical axis, as in Teece (1986), measures how those who possess the technology (the innovator or possibly its imitators) are positioned vis a vis those firms that possess required specialized assets. The horizontal axis measures the "tightness" of the appropriability regime. Weak regimes are further subdivided according to how the innovator and imitators are positioned vis a vis each other.

For discrete technologies, the original PFI framework emphasized that in the case of a strong appropriability regime, it is unlikely for firms other than the innovator to profit from the invention, therefore contracting (via technology licensing or selling) was an available strategy (cells 1 and 3). In the case of the enabling technology, contracting is still the best solution under a strong appropriability regime, but its success might be lower than in the case of a discrete technology for farther application domains (cells 2 and 4). This is even more problematic when the innovator is in a weak position vis a vis the owner of complementary assets (cell 4). Yet compared to the case of a discrete technology, the innovator with an enabling technology can choose among multiple application sectors where the technology could be applied. More options to choose from might improve the odds for the innovator.

Even more critical is the case of a firm operating under a weak appropriability regime, particularly when innovators and imitators are positioned disadvantageously vis a vis the owners of complementary assets (cells 7 through 10). When the innovator is favorably positioned versus imitators with respect to commissioning complementary assets (cell 7), the original PFI framework recommends integration, which will result in positive returns for the innovator.

-----Insert Figure 2 about here-----

In the case of an enabling technology (cell 9), integration is a less-profitable strategy. Integration is still the dominant strategy to protect the innovation; however, this strategy is likely to be less successful. This is due to the value/applicability and cost/applicability tradeoffs that characterize enabling technologies. To be applicable across settings, an enabling technology is likely to require higher design costs and be characterized by a lower unit value in each specific setting compared to technologies that have been fine tuned for that setting. With a higher fixed design cost and a lower value in each application, the pioneer's ability to profit adequately[8] from an enabling technology is possible if the technology is applied across multiple settings (i.e., "broad horizontal scope of commercialization"). However, due to the high costs likely associated with the acquisition of complementary assets across diverse settings and the likely cash constraints, the innovator who chooses to integrate is likely to do it in a limited number of settings (i.e., "narrow horizontal scope of commercialization"). If so, the innovator could lose in each setting to firms with discrete technologies, which might be able to deliver more value to the users in those settings. The extent to which this is likely depends on how less valuable the enabling technology is compared to the alternative discrete technologies available in those settings.

When the innovator is positioned poorly versus imitators with respect to commissioning complementary assets (cell 8), the original PFI framework recommended contracting to limit exposure, because this situation might lead to losing to imitators. In the case of enabling technologies too (cell 10), this is not so rosy a perspective. It is compensated partially by the fact that an enabling technology provides the opportunity to contract with a higher number of application sectors (i.e. contracting with broad horizontal scope). In line with this intuition, a recent stream of research has explored this business model of innovators focusing on licensing their enabling technology to the downstream manufacturers of products across settings—referred to as *specialization in generality* (Gambardella & McGahan, 2010; Conti et al., 2019a). Conti et al. (2019a) suggest and empirically test that when downstream entry is not

[8] As before, an adequate or fair profit ensures that the innovation captures a sufficiently large share of the total surplus to incentivize continued investment in high-spillover and high-impact enabling technologies.

convenient, innovators may find it profitable to save resources by not entering downstream markets and specialize in licensing the enabling technology to the various downstream markets in which it can be applied. For example, in the early 1990s, a leading company such as IBM pulled out of the PC and other downstream markets to become a provider of general technological solutions, which was its major competence (Gerstner, 2002); many laser firms provide another similar example (Conti et al., 2019a). They also show that contracting an enabling technology is mostly appropriate when the innovator can contract its technology with a broad horizontal scope.

To help innovators of enabling technologies navigating the complexity of these strategic options, we formally extend the PFI framework to the case of enabling technologies (Figure 3). The first question that an innovator should consider is whether the technology developed is discrete or enabling. If the former, the original PFI framework applies. If the latter, like in the original PFI framework, the next question concerns whether a dominant design for the enabling technology has emerged already. If not, waiting for the dominant design to emerge could still be the dominant strategy, except that, in the case of an enabling technology, the wait actually could never lead to an outcome due to the mentioned coordination failure that characterizes enabling technologies. Policy and regulatory support therefore would be needed to facilitate the process.

-----Insert Figure 3 about here-----

If a dominant design for the enabling technology has already emerged and the innovator possesses the critical complementary assets (or the resources to acquire them) in-house, the strategy of integration, with a broad horizontal scope—based on commercializing the technology in as many application sectors as possible—would be sensible and perhaps profitable.[9] But for the vast majority of firms that cannot enjoy such fortunate position, the next key question concerns the strength of the appropriability regime in

[9] The PFI framework suggested that complementary asset specialization tends to act as a protection mechanism against imitation: ownership of assets fine-tuned perfectly to the focal technology might be difficult to replicate. But because enabling technologies are—by definition—technologies more upgradable and adaptable than others, it is possible that they might not require to be used with specialized assets to the same extent of discrete technologies. So, asset specialization does not necessarily help the innovator of an enabling technology.

the focal industry. If it is high, the enabling technology potentially could be commercialized successfully via contracting it out.

However, two additional questions that were not present in the PFI framework become relevant here. The first concerns the level of performance of the enabling technology compared to the alternative discrete technologies available in different settings (the abovementioned difference between V_{Ei} and V_{D}). If the enabling technology performance in each individual setting (V_{Ei}) is particularly low compared to the performance of a discrete technology in the same setting (V_{D}), profiting from innovation for the owner of the enabling technology could be more difficult. In Figure 2, we refer to this question as to "sufficient value of the enabling technology (compared to discrete one)?"

Contracting out the technology as it is to buyer-firms across settings would be possible, but would be unlikely to generate high profits, because the technology would not be appealing to buyer-firms due to its lower value compared to discrete technologies in the same setting. The innovator could then go through many rounds of adaptation and fine-tuning to make it competitive with other discrete technologies in those settings. Depending on how expensive this process is, it could depress its profitability. An interesting example here is the case of complex (enabling) technologies (i.e., those characterized by many components and interdependencies among them). The cost of adapting a simpler (enabling) technology across different settings is likely to be low. This implies that contracting the technology across settings is likely to be a convenient option. But adapting a more complex enabling technology across settings would likely be more expensive, as complex technologies are characterized by many interdependent components, and their performance easily deteriorates if even only a handful aspects are missed (Kapoor & Agarwal, 2017; Rivkin, 2000). It follows that profiting from complex enabling technologies might be problematic.

Another relevant question concerns whether innovators with the enabling technology have complementary knowledge in the application sectors, which is meant to reflect their actual ability to exploit, monitor, and enforce appropriability across differing settings, as per our discussion on appropriability in section II. In Figure 2, we refer to this as to "complementary knowledge across application sectors?" If innovators with an enabling technology lack these relevant skills, their ability to exploit the strength of the appropriability regime across settings will be low (r_{Ei} decreases as i increases), and therefore licensing out the technology, especially in distant settings, might not result in reasonable profits. In anticipation of this, the enabling technology might not be developed in the first place.

The two points above suggest that profiting from enabling technologies by contracting them out with a broad horizontal scope can more likely be a profitable strategy for innovators whose performance compares favorably to alternative discrete technologies and who have a large complementary knowledge base in application sectors. Focused innovators and innovators in technological contexts characterized instead by high complexity might need more support, irrespective of their size.

Finally, when the appropriability regime is weak, complementary assets are not available, and cash resources are limited, a last concern for an innovator with an enabling technology is the extent to which imitators or competitors are in a relatively better position. If they are contracting with a narrow horizontal scope, partnering with a selected firm to access its assets is an available strategy. This strategy, though, is suboptimal, as profits would likely accrue more easily to the better-endowed partner; and, because of this, it might lead to a lower likelihood that the innovator develops the enabling technology in the first place. If the innovator instead is better positioned than competitors, commercializing the technology via integration could still be viable. But due to the innovator's limited cash resources, integration in only a few settings would be possible (narrow horizontal scope). The latter is unlikely to be a winning strategy with an enabling technology. The innovator's profits are squeezed simultaneously by the lower value that can be offered (and, consequently, lower price that can be commanded) to the customers in each application sector and by the lower number of application sectors entered.

The resulting comprehensive framework that emerges from our extension of the PFI framework to the case of enabling technologies does not only provide strategic guidance to the innovator of an enabling technology. It also provides guidance regarding the classes of innovators and technologies that might require regulatory and policy support. Importantly, Figure 3 shows that not only smaller innovators less endowed with cash resources (as in the original PFI framework) might find capturing sufficient value from innovation difficult. Large, yet more knowledge-focused, innovators (which do not have complementary knowledge across settings and might therefore be less likely to exploit the strength of the appropriability regime as efficiently across settings) and innovators of more complex technologies (which require more adaptation and, therefore, higher costs to be applied across settings) might face substantial challenges in capturing value from enabling technologies. This implies that enabling technologies in those cases are less likely to be developed in the first place. To the extent that the contribution of these classes of innovators and technologies is important to public welfare, regulatory and policy support needs to be designed accordingly.

V. Discussion and Implications

Thirty years after its publication, the PFI framework has continued to have a considerable impact on the field of technology management. We focused on how PFI applies in the context of enabling technologies. Although previous studies have drawn attention to the importance of enabling technologies, they tend to focus on value creation rather than value capture. To our knowledge, our attempt to advance the PFI framework to the special context of enabling technologies has not been done before.

Our main argument has been that, with enabling technologies, the nature of the technology and its application potential need to be considered with some granularity to illuminate idiosyncratic value-capture issues, at least when compared to value-capture in the context of discrete technologies. We have elaborated on the special characteristics of profiting from enabling technologies, supported by illustrative evidence based on the analysis of data from the Patval survey. In this respect, the highlight of this paper from a strategic management perspective is that enabling technologies create a more uncertain and complex scenario for firms. In particular, the relationship between the strength of the legal appropriability regime and the commercialization choice does not hold uniformly for enabling technologies. Innovators with enabling technologies are likely less able to enjoy the benefits of a strong appropriability regime. We also suggested that even under a weak appropriability regime, the benefits of integration are effectively lower, because integration is likely to be limited by cash constraints for the owner of an enabling technology.

Building on these insights, we have offered an extension of Teece's (1986) original PFI framework to accommodate the important case of enabling technologies. This extended framework has clear implications for the design of business models and supporting strategies. PFI suggested that a key decision facing an innovator is whether to merely focus on the development and contracting of innovation with other firms, or rather to vertically expand the scope of its activities by incorporating its invention into a product and selling it to final consumers in the product market.

Here we outlined how, in the case of enabling technologies, neither integration nor contracting are straightforward choices. Because of the breadth of opportunities offered by enabling technologies, broad integration is feasible for few innovators. Despite prior theoretical work having demonstrated that the unfolding of an enabling technology gives rise to increasing returns-to-scale (Bresnahan & Trajtenberg, 1995), technological and regulatory forces, over time, have significantly reduced the diffusion and the role of dominant, highly diversified firms (Bresnahan & Trajtenberg, 1995; Arora, Belenzon & Patacconi, 2018). It might also be argued that—in the real world—the size of an integrated firm's capability set is likely to be limited, despite its level of diversification. A strategy of integration with a broad horizontal scope would likely substitute "one myopic decision maker for a plurality of them," and inventive efforts could be therefore much more confined (Merges & Nelson, 1994, p.6). Whereas such a firm would have the internal incentives to develop this technology, it might not be sufficiently innovative downstream and could still benefit from the cross-fertilization that occurs via accessing other firms' complementary capabilities (Ahuja, Lampert & Novelli, 2013).[10]

Licensing could be a way to address this issue and generate downstream technology contributions. Assuming a supportive judicial system, the breadth of applicability of an enabling technology might be able to compensate at least partially for the adverse effect of weak appropriability. When contracting with different downstream markets, licensors without regulatory or contractual obligations may be able to negotiate limited exclusivities with firms that don't compete among each other. The price that the

[10] Kitch (1977) seems to believe otherwise, believing that having a sole player develop all the applications—without fear of external encroachment—is likely better.

licensees might be willing to pay for the technology will be enhanced (Gambardella & Giarratana, 2013). But we have already explained how this might still lead to underinvestment. Private and social returns need to equalize to incent the level of innovation that is right for society.[11]

Overall, we believe that our paper has opened up new angles for understanding how to profit (and how to lose) from innovation. Our framework sheds light on some of the private challenges accruing to the innovators of enabling technologies. The policy implications of these private challenges are of fundamental importance. Policymakers must recognize that the economic contributions of enabling technologies for the economy can be high; but innovators face special challenges with respect to capturing enough value from their technologies, which implies they will tend to underinvest in such technologies without any government support and without appreciation and understanding by the courts.

Interestingly, prior research has overlooked this question. The policy-oriented literature on patent scope, for instance, has generally associated a higher degree of appropriability to patents whose value was spanning multiple domains (e.g., Kitch, 1977; Gilbert & Shapiro, 1990; Klemperer 1990). This conclusion was derived from a variety of assumptions, such as that the costs of developing a technology spanning multiple domains were the same as the costs of developing a more dedicated one; that a more enabling technology could lead to more value capture by allowing the innovator to generate returns in multiple product markets; and that all innovators would have the capabilities and assets to profit equally in each of the related product markets (for a review, see Novelli, 2015). The assumptions made in the prior literature referenced in this paragraph do not necessarily hold, as illustrated in this paper.

We hope this paper stimulates further reflections on whether government should incent and otherwise support investment in enabling technologies. Perhaps court should grant higher levels of protection to inventors of more (versus less) enabling technologies. Stronger patent protection enables the market for technology to work better and for open innovation (via licensing) models to flourish. Identifying mechanisms that can increase potential rewards to breakthrough innovators of enabling

[11] See Mansfield et al. (1977) for a discussion of private and social returns to innovation.

technologies ought to lead to an increase in the generation of enabling technologies in the economy. This could potentially increase social welfare. Enabling technologies, like general purpose technologies, are precious to society, yet it is difficult for the innovator to capture a proportionate reward. A possible concern might be that broad patents might result in intellectual property protection that is too broad (Heller & Eisenberg, 1998). However, there is little evidence to suggest that patent thickets cannot be navigated (Barnett, 2017; Teece, 2017b). We hope our study stimulates further exploration of this subject and lays the groundwork for further improvements to the profiting from innovation framework and its related implications for both firm strategy and public policy.

REFERENCES

Ahuja G, Lampert CM, Novelli E (2013) The second face of appropriability: Generative appropriability and its determinants. *Academy of Management Review* 38(2):248-269.

Arora A, Belenzon S, Patacconi A (2018) The decline of science in corporate R&D. *Strategic Management Journal* 39(1):3-32.

Arora A, Fosfuri A, Gambardella A (2001) Markets for technology: The economics of innovation and corporate strategy. *MIT press*.

Arrow KJ (1962) The economic implications of learning by doing. *The Review of Economic Studies* 29(3):155-173.

Barnett J (2017) Has the Academy Led Patent Law Astray. *Berkeley Technology Law Journal* 32(4).

Bresnahan TF (2012) Generality, recombination, and reuse. In: Lerner, J., Stern, S. (Eds.), The Rate and Direction of Inventive Activity Revisited. University of Chicago Press, Chicago, pp. 611–656.

Bresnahan T, Gambardella A (1998) The Division of Inventive Labor and the Extent of the Market. Working Paper, Stanford University, Department of Economics.

Bresnahan TF, Trajtenberg M (1995) General purpose technologies' Engines of growth'? *Journal of Econometrics 65*(1):83-108.

Chang HF (1995) Patent scope, antitrust policy, and cumulative innovation. *The RAND Journal of Economics* 34-57.

Cohen WM, Nelson RR, Walsh JP (2000) Protecting their intellectual assets: Appropriability conditions and why US manufacturing firms patent (or not). Working paper, National Bureau of Economic Research.

Conti R, Gambardella A, Novelli E (2019a) Specializing in generality: firm strategies when intermediate markets work. *Organization Science* 30(1):126-150.

Conti R, Gambardella A, Novelli E (2019b). Specializing in general purpose technologies as a firm long-term strategy. *Industrial and Corporate Change* 28(2):351–364.

Echelon Corporation (2018). Adesto Completes Acquisition of Echelon. *PR Newswire* (September 14, 2018), available at: https://www.prnewswire.com/news-releases/adesto-completes-acquisition-of-echelon-300712837.html

Gambardella A, Giarratana M (2013) General technological capabilities, product market fragmentation, and markets for technology. *Research Policy* 42(2):315–325.

Gambardella A, McGahan AM (2010) Business-model innovation: General purpose technologies and their implications for industry structure. *Long range planning* 43(2-3):262-271.

Gerstner L (2002) *Who Says Elephants Can't Dance? Inside IBM's Historic Turnaround (*Harper, New York).

Gilbert R, Shapiro C (1990) Optimal patent length and breadth. *The RAND Journal of Economics* 21(1):106-112.

Hall B (2005) A note on the bias in herfindahl-type measures based on count data. *Revue d 'économie industrielle* 110(1):149-156.

Hall BH, Jaffe AB, Trajtenberg M (2001) The NBER patent citation data file: Lessons, insights and methodological tools (No. w8498). *National Bureau of Economic Research*.

Heller MA, Eisenberg RS (1998) Can patents deter innovation? The anticommons in biomedical research. *Science* 280(5364):698-701.

Hoisl K, Mariani M (2016) It's a man's job: Income and the gender gap in industrial research. *Management Science* 63(3):766-790.

Jones B (2012) Comment on generality, recombination, and reuse. In: Lerner, J., Stern, S. (Eds.), The Rate and Direction of Inventive Activity Revisited. University of Chicago Press, Chicago, pp. 656–661. http://www.nber.org/chapters/c12375. (Accessed 29 December 2016).

Kapoor R, Agarwal S (2017). Sustaining superior performance in business ecosystems: Evidence from application software developers in the iOS and Android smartphone ecosystems. Organization Science, 28(3), 531-551.

Kim DJ, Kogut B (1996) Technological platforms and diversification. *Organization Science* 7(3): 283-301.

Kitch EW (1977) The nature and function of the patent system. *The Journal of Law and Economics* 20(2):265-290.

Klemperer P (1990) How broad should the scope of patent protection be? *The RAND Journal of Economics* 21(1):113-130.

Leih S, Teece DJ (2017) Antitrust, Standard Essential Patents, and the Fallacy of the Anticommons Tragedy: Legal and Industrial Policy Concerns. *Berkeley Technology Law Journal* 32:1301.

Levin RC, Klevorick AK, Nelson RR, Winter SG, Gilbert R, Griliches Z (1987) Appropriating the returns from industrial research and development. *Brookings papers on economic activity* 1987(3):783-831.

Lipsey RG, Bekar C, Carlaw K (1998) The Consequences of Changes in GPTs. Helpman E, ed. *General Purpose Technologies and Economic Growth* (MIT Press, Cambridge and London).

Lipsey RG, Carlaw KI, Bekar C (2005) *Economic transformations: General purpose technologies and long term economic growth* (Oxford University Press, Oxford).

Malmgren HB (1961) Information, expectations and the theory of the firm. *The Quarterly Journal of Economics* 75(3):399-421.

Mansfield E, Rapoport J, Romeo A, Wagner S, Beardsley G (1977) Social and private rates of return from industrial innovations. *Quarterly Journal of Economics* 91(2): 221–240.

Merges RP, Nelson RR (1990) On the complex economics of patent scope. *Columbia Law Review* 90(4):839-916.

Merges RP, Nelson RR (1994) On limiting or encouraging rivalry in technical progress: The effect of patent scope decisions. *Journal of Economic Behavior & Organization* 25(1):1-24.

Montgomery CA, Wernerfelt B (1988) Diversification, Ricardian rents, and Tobin's q. *The Rand Journal of Economics* 19(4):623-632.

Nelson RR (1959) The simple economics of basic scientific research. *Journal of Political Economy* 67(3):297-306.

Novelli E (2015) An examination of the antecedents and implications of patent scope. *Research Policy* 44(2):493-507.

Rivkin JW (2000) Imitation of complex strategies. *Management science*, 46(6), 824-844.

Rosenberg N (1963) Technological change in the machine tool industry, 1840–1910. *The Journal of Economic History* 23(4):414-443.

Rosenberg N (1998) Uncertainty and technological change. Neef D, Siesfeld GA, Cefola J, *The economic impact of knowledge* (Butterworth Heinemann, Woburn), 17-34.

Rotolo D, Hicks D, Martin BR (2015) What is an emerging technology? *Research Policy* 44(10):1827-1843.

Schumpeter JA (1950) *Capitalism*, *Socialism and Democracy* (Harpers and Brothers Publishers, New York).

Teece DJ (1986) Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy. *Research Policy* 15(6):285-305.

Teece DJ (2006) Reflections on profiting from innovation. *Research Policy* 35(8):1131-1146.

Teece DJ (2017a) The Tragedy of the Anticommons Fallacy. *Berkeley Law and Technology Journal* 32(4).

Teece, DJ (2017b). A capability theory of the firm: an economics and (strategic) management perspective. *New Zealand Economic Papers* 53(1):1-43.

Teece DJ (2018a) Profiting from innovation in the digital economy: Enabling technologies, standards, and licensing models in the wireless world. *Research Policy* 47(8):1367-1387.

Teece DJ (2018b) Enabling Technology, Social Returns to Innovation, and Antitrust: The Tragedy of Depressed Royalties. *CPI Antitrust Chronicle* (June 2018), https://dev.competitionpolicyinternational.com/enabling-technology-social-returns-to-innovation-and-antitrust-the-tragedy-of-depressed-royalties/

Teece, DJ (2018c) Enabling Technologies and the Underinvestment Problem. Retrieved May 31, 2020, https://www.ipwatchdog.com/2018/07/10/enabling-technologies-underinvestment-problem/id=98824/

Thoma G (2008) Striving for a large market: evidence from a general purpose technology in action. *Industrial and Corporate Change* 18(1):107-138.

Torrisi S, Gambardella A, Giuri P, Harhoff D, Hoisl K, Mariani M (2016). Used, blocking and sleeping patents: Empirical evidence from a large-scale inventor survey. *Research Policy* 45(7):1374-1385.

Williamson OE (1975) *Markets and hierarchies* (Free Press, *New York*).

Winter SG (2006) The logic of appropriability: From Schumpeter to Arrow to Teece. *Research Policy* 35(8):1100-1106.

TABLES

Table 1. Variable operationalization

Variable	Operationalization
Enabling technology	To distinguish between enabling and discrete technologies, we used the established patent's generality index elaborated by Hall, Jaffe, and Trajtenberg (2000). The measure is built based on two characteristics of the US patent system: (i) each patent is classified in a main technological class based on the technological domain to which the patented technology contributes; and (ii) every time a follow-up invention builds on a focal patent, the inventor of the follow-up invention is expected to cite the focal patent, originating in this way "a forward citation." Thus, the extent to which a patent is applicable across domains can be identified by measuring the dispersion of the patent's forward citations across technological classes: patents more broadly applicable will be more likely to receive forward citations across contexts as opposed to narrowly focused in one. Applying this logic to our context, we suggest that Hall et al.'s (2001) measure can provide an indication of the extent to which a patent is enabling in its nature. Hence, we followed these authors and employed the following process. For each of the US patent equivalents, we collected data on the forward citations it received and calculated the following measure: Generality= $= \left(1 - \sum_{j=1}^{J} \left(\frac{N_{ij}}{N_i}\right)^2\right) x \ \frac{N_i}{N_i - 1}$ where N_i denotes the number of forward citations to a patent, and N_{ij} is the number received from patents in class j (at the IPC main-classes level of analysis). The measure includes an adjustment for the natural downward bias that might occur when the total number of citations to a patent is small (Hall, 2005). Finally, we calculated the median of the generality for all patents in our sample and classified as "enabling technologies" those patents having a generality higher than the sample median; and as "discrete" (not enabling technologies) those patents reporting a generality score lower or equal to the median.
Dependent variables	
Contract (selling or licensing the technology)	Dummy variable valued 1 based on whether the response to either one of the following questions of the Patval survey was equal to "Yes": "*Has this patent been licensed by (one of) the patent-holder(s) to an independent party?"; "Was the ownership right to the patent sold to another party not related to the original owner(s) or applicant(s)?"*
Integration	Dummy variable valued 1 in case of a positive response to the following question of the Patval survey (and 0 otherwise): *"Have the applicant(s) or affiliated parties ever used this patented invention commercially, i.e., in a product, service, or manufacturing process?"*
Independent variables	
Strength of the appropriability regime	Index at the industry-country level. We obtained industry-level appropriability strength data from the Carnegie Mellon Survey (Cohen et al,. 2000) and country-level appropriability strength data of the Fraser Institute Index on the quality of different countries' national legal systems. For each inventor in the sample, we identify the main industry and the country of reference of the invention from the Patval survey. The variable *strength of the appropriability regime* was calculated as the product of the strength of the appropriability regime in the industry and country of reference of the inventor.
Availability of complementary assets	Dummy variable valued 1 based on whether both responses to the following items of the Patval survey were higher than 4 on a 5-point scale: *"Please rate the extent to which you agree or disagree with the following statements about the organization in which the invention was made: The organization had all the complementary resources to make the invention a technical success; The organization had all the resources to turn the invention into something economically valuable (e.g., new product, process or something else)."*
Paradigmatic phase	Dummy variable valued 1 in case of a positive response to the following question of the Patval survey (and 0 otherwise): *"Does this invention utilize or build upon technical standards, such as those published by ISO or an industry association?"* The variable took value 1 in case of a positive response; 0, otherwise.
Controls	
Inventor age	Logarithm of the inventor's age at the time of the invention; obtained from the Patval survey.
Inventor experience	Number of years elapsed between the inventor's first invention and the focal priority date; obtained from the Patval survey.
Inventor employed	Dummy variable valued 1 if the inventor was employed at the time of the invention, 0 otherwise; obtained from the Patval survey.
Patent granted	Dummy variable valued 1 if the patent had been granted already, 0 otherwise. Obtained from the Patval survey.
US patent	Dummy variable valued 1 if the country of the invention is the US. Obtained from the Patval survey.
Organization age dummies	Dummy variables indicating the age of the organization the employee was affiliated with at the time of the invention, as classified in four categories: "<5 yrs," "5-10 yrs," "11-20 yrs," ">20 yrs"; obtained from the Patval survey.
Economic value dummies	Dummy variables for the economic value of the patent, based on the classification of the patent into four categories depending on the answer to the following question of the Patval survey: *"In comparison with other patents in your industry or technological field, how would you rate the economic value of this patent? 1.Top 10%; 2. Top 25%, but not top 10%; 3. Top 50%, but not top 25%; 4. Bottom 50%."*
Year dummies	Dummy variables indicating the year in which the patent was filed; obtained from the Patval survey.
Organization size dummies	Dummy variables indicating the size of the organization with which the employee was affiliated at the time of the invention, based on the number of employees of the firm with which the inventor was affiliated, classified into the following categories: "1-49 employees," "50-99 employees," "100-249 employees," "250-499 employees," "500-999 employees," "1000-4999 employees," "5000 and more employees"; obtained from the Patval survey.

Table 2. Summary statistics and pairwise correlations

		Obs	Mean	S.D.	Min	Max	1	2	3	4	5	6	7	8	9	10
1	Contract	7,290	0.086	0.281	0.000	1.000	1.000									
2	Integration	7,290	0.471	0.499	0.000	1.000	0.112	1.000								
3	Availability of complementary assets	7,290	0.445	0.497	0.000	1.000	-0.031	0.166	1.000							
4	Strength of the appropriability regime	7,290	14.563	2.337	6.136	23.477	-0.008	-0.030	0.053	1.000						
5	Paradigmatic Phase	7,290	0.165	0.371	0.000	1.000	0.025	0.100	0.040	-0.044	1.000					
6	Inventor age	7,290	3.741	0.228	2.833	4.431	0.092	0.017	0.079	-0.011	0.015	1.000				
7	Inventor experience	7,290	11.360	9.562	0.000	61.000	0.068	0.007	0.022	-0.010	-0.011	0.668	1.000			
8	Inventor employed	7,290	0.944	0.230	0.000	1.000	-0.104	-0.031	0.035	0.047	-0.011	-0.157	-0.145	1.000		
9	Patent granted	7,290	0.357	0.479	0.000	1.000	-0.015	0.075	0.041	0.022	-0.024	-0.017	-0.025	0.004	1.000	
10	US patent	7,290	0.250	0.433	0.000	1.000	0.074	-0.007	0.107	-0.079	0.016	0.272	0.151	0.001	-0.151	1.000

Table 3. Bivariate probit model on the probability of commercializing the technology via contract and/or via integration

	Full Sample		Discrete technologies		Enabling technologies	
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Contract	Integration	Contract	Integration	Contract	Integration
Strength of the appr. regime	0.035***	-0.018***	0.050***	-0.024***	0.022	-0.012
	(0.012)	(0.007)	(0.018)	(0.009)	(0.017)	(0.009)
Availability of complementary assets	0.891***	0.436***	0.884**	0.419***	0.897**	0.463***
	(0.276)	(0.031)	(0.392)	(0.044)	(0.394)	(0.044)
Availability of complementary assets X Strength of the appr. regime	-0.068***		-0.070***		-0.067**	
	(0.019)		(0.026)		(0.027)	
Paradigmatic phase	0.078	0.304***	0.106	0.217***	0.053	0.426***
	(0.057)	(0.041)	(0.077)	(0.055)	(0.086)	(0.062)
Inventor age	0.454***	-0.068	0.527***	-0.118	0.361*	-0.037
	(0.133)	(0.092)	(0.192)	(0.132)	(0.188)	(0.131)
Inventor experience	0.000	-0.000	-0.001	0.001	0.001	-0.002
	(0.003)	(0.002)	(0.004)	(0.003)	(0.004)	(0.003)
Employed	-0.008	-0.006	0.138	0.109	-0.184	-0.156
	(0.091)	(0.076)	(0.132)	(0.104)	(0.127)	(0.111)
Patent granted	0.005	0.187***	0.030	0.167***	-0.014	0.205***
	(0.047)	(0.032)	(0.067)	(0.045)	(0.067)	(0.045)
US	0.187***	-0.033	0.154**	-0.057	0.229***	0.003
	(0.051)	(0.038)	(0.073)	(0.053)	(0.073)	(0.054)
Organization age dummies	Included	Included	Included	Included	Included	Included
Economic value dummies	Included	Included	Included	Included	Included	Included
Year dummies	Included	Included	Included	Included	Included	Included
Organization size dummies	Included	Included	Included	Included	Included	Included
Constant	-3.186***	0.137	-3.612***	-0.310	-2.718***	0.563
	(0.597)	(0.427)	(0.865)	(0.636)	(0.836)	(0.602)
Observations	7,290	7,290	3,661	3,661	3,629	3,629

Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

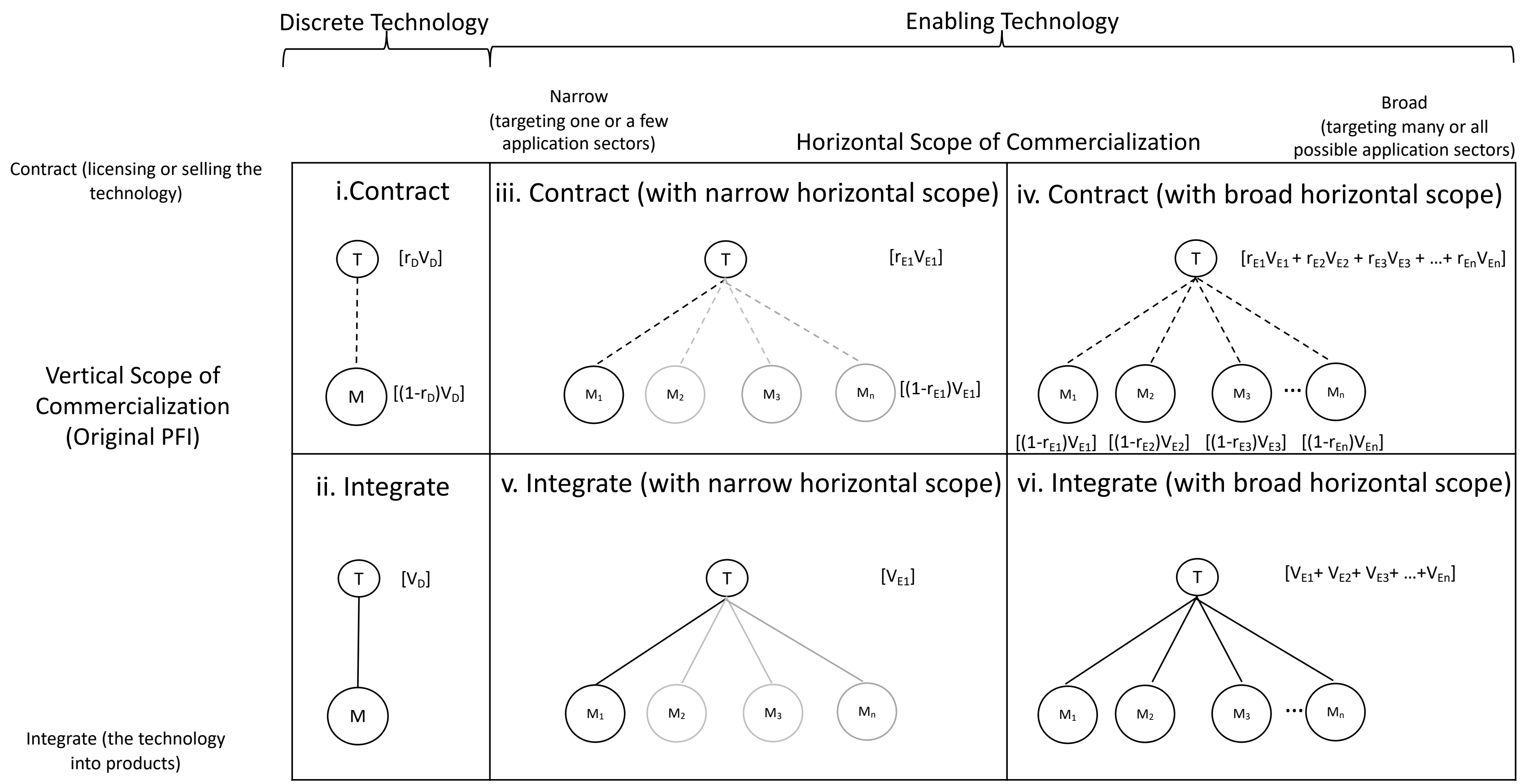
Table 4. Marginal effects

	Full Sample		Discrete technologies		Enabling technologies	
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Contract	Integration	Contract	Integration	Contract	Integration
Strength of the appr. regime if complementary assets =0	0.005***	-0.007***	0.008***	-0.009***	0.003	-0.004
Strength of the appr. regime if complementary assets =1	-0.004**	-0.007***	-0.003	-0.009***	-0.006**	-0.004
Complementary assets if strength appr. regime = min	0.068***	0.165***	0.055*	0.158***	0.081*	0.174***
Complementary assets if strength appr. regime = max	-0.106***	0.162***	-0.126***	0.153***	-0.087**	0.173***
Paradigmatic phase	0.012	0.114***	0.016	0.081***	0.008	0.158***

*** p<0.01, ** p<0.05, * p<0.1

FIGURES

Figure 1. Innovator's strategies to profit from discrete and enabling technologies



T=technology development
M=embodiment of the technology into products

V_D=Total value of the vertical chain
r_D=share accruing to the innovator
(r_D=1 in the case of integration)

$V_{E1}, V_{E2}, V_{E3}, \ldots V_{En}$ =total value in each vertical chain
$r_{E1}, r_{E2}, r_{E3}, \ldots r_{En}$ =share accruing to the innovator for each vertical chain
(r_E=1 in the case of integration)

Dashed lines characterize contracting
Solid lines characterize integration
Grey lines characterize settings that the innovators could potentially target but have chosen not to

Figure 2. Contract and integration strategies and outcomes for innovators. This is adapted from Figure 11 in Teece (1986).

	Strong legal/ technical appropriability	Weak legal/technical appropriability	
		Innovator excellently positioned versus imitators with respect to commissioning complementary assets	Innovator poorly positioned versus imitators with respect to commissioning complementary assets
Innovators and imitators advantageously positioned vis a vis independent owners of complementary assets	1. Discrete technology= Contract: Innovator will win.	5. Discrete and enabling technology= Contract: Innovator should win.	6. Discrete and enabling technology= Contract: Innovator or imitator will win; asset owners won't benefit.
	2. Enabling technology= Contract: But innovator's ability to exploit the strength of the appropriability regime might be lower for applications that are far from its core knowledge domain or that are not yet known.		
Innovators and imitators disadvantageously positioned vis a vis independent owners of complementary assets	3. Discrete technology= Contract if can do so on competitive terms; integrate if necessary: Innovator should win; may have to share profits with asset holder.	7. Discrete technology= Integrate: Innovator should win.	8. Discrete technology= Contract (to limit exposure): Innovator will gradually lose to imitators and/or asset holders.
	4. Enabling technology= Contract: But, as above, innovator's ability to exploit the strength of the appropriability regime might be lower, and this is worsened by the weak position vis a vis independent owners of assets. Yet, compared to the case of a discrete technology (3), the innovator with an enabling technology can choose among multiple application sectors that can be targeted, possibly improving the odds for the innovator.	9. Enabling technology= Integrate in as many application sectors as cash constraints allow ("integrate with broad horizontal scope"). Due to cash constraints, integration in only a few domains is more likely. But it might lead the innovator to lose to firms with a discrete technology that might be able to create more value for users in each application sector.	10. Enabling technology= Contract targeting multiple-application sectors to limit exposure (contract with broad horizontal scope). Innovator may gradually lose to imitators, but might be able to compensate at least to some extent by exploiting the broad applicability of the technology, which provides more opportunities of returns.

Figure 3. Revised PFI framework. Flow chart for integration versus contract decision in the case of discrete and enabling technologies.