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Thesis title:

ESSAYS ON CORPORATE SCIENCE AND TECHNOLOGICAL CHANGE

PhD in	BUSINESS ADMINISTRATION AND MANAGEMENT
Cycle	XXX
Student's Advisor	PROF. DR. ANDREA FOSFURI
Calendar year of thesis defense	2020

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Essays on Corporate Science and Technological Change

Submitted by

Hakkı Doğan Dalay

as part of the partial requirements for a PhD Degree in Business Administration and Management

at Bocconi University in Milan, Italy

December 9th, 2019

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Introduction

The current manuscript is comprised of three chapters submitted in accordance with the partial requirements of a PhD dissertation in Business Administration and Management at Bocconi University in Milan, Italy. The three chapters explore issues around the role and use of science in manufacturing firms, incumbent response to discontinuous technological change and the role of science in responding to such changes.

In the first chapter of the dissertation, I explore the organizational aspect of scientific assets in large corporate groups. Leveraging on earlier findings in the literature on economics of innovation and innovation strategy literatures, I advance the argument that the organization of scientific assets leads to a trade-off. According to this, corporate groups face a decision on whether to organize scientific assets separately on its own or together with inventive activities. I test this argument based on a comprehensive data set on the inventive and scientific activities of large corporate groups in Europe, where I measure corporate science by publications affiliated with corporate business units. I also trace the inventive activities of these firms in patent documents and the use of science in patents by the non-patent literature citations in patent documents. By collocating scientific and inventive activities together, corporate groups can make better use out of their scientific findings in their inventive activities. However, this comes at the cost of the quality of the research produced by these firms. When science is carried out in separate locations, firms make less use out of the scientific findings in their patents. I discuss the contribution of these findings related to the literature on economics of innovation.

In the second chapter, I explore the responses of large incumbents facing technological change. In the aftermath of a discontinuous technological change, large incumbents with entrenched positions in the earlier technology need to respond to the emergence of the new technology. In this context, an important variable that has not received much attention is the ownership

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structure of incumbents. More specifically, I look at the case when incumbents have a mixed ownership structure, whereby the shares of the incumbents are partly privately held and partly held by the government. The chapter advances the argument that mixed ownership is associated with lower responsiveness to digitization. This conjecture is based on the argument that CEOs and top management of corporations with mixed ownership are exposed to conflicting views on how companies should address the challenges posed by technological change, thereby making them more likely to maintain the status quo. Based on a dataset of European telecommunications providers, findings provide support to the notion that incumbent operators with mixed ownership respond substantially less aggressively to the digital challenge compared to firms that are either fully private or in which the government owns a majority of shares. In addition, the challenges resulting from mixed ownership are more accentuated when trying to adopt to technological change with new technologies sourced from outside the company.

In the third chapter of this dissertation, I look at the role of science in responding to discontinuous technological change. Leveraging on earlier findings in the literature, I argue that acquiring scientific knowledge increases in importance in the aftermath of a technological change, evident from the cumulative abnormal returns resulting from acquisition deals involving targets with scientific assets. The underlying argument for this finding is that giving up on internal scientific research comes at the cost of losing the ability to identify and also assimilate new knowledge that is needed to survive in a new technological regime. Leveraging on earlier findings in the literature, I also argue that science has a changing role in the aftermath of a technological change as it does not suffice to acquire external knowledge only. For this chapter with ongoing work, I share my preliminary findings based on data from the U.S. pharmaceutical industry in 1990s.

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DIVISION OF INNOVATIVE LABOR AND THE ORGANIZATION OF CORPORATE SCIENCE AND INVENTION

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Abstract

We study how business groups organize their scientific and inventive activities across business units. Theoretically, isolating science in a separate business unit allows for better governance, stronger incentives and greater ability to attract top scientists. On the other hand, collocating science and invention in a single unit enhances knowledge flows between the two activities thereby increasing the ability to incorporate science into inventions. To analyze this tradeoff, we develop new systematic data on the science (publications) and invention (patents) activities of business units in Europe, as well as their ability to utilize the science they produce in their inventions (patent citations to scientific publications). We find that when science and invention are collocated, business units not only develop more science-based inventions, but also display greater ability to absorb extramural science. Instead, dividing science and invention into separate business units leads to higher quality scientific research, but this science is less useful for the inventive activities of the corporation.

KEYWORDS: science, invention, use of science, organization of innovation, business groups

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Introduction

Science, by producing non-rivalrous inputs into technological innovation, is a key engine of economic growth (Romer, 1990). Science differs from other knowledge production systems in several dimensions. It allows for great discretion in choosing research projects and is often distant from practical ends, it entails large degrees of uncertainty in outcomes, and it has a reward structure based on establishing intellectual priority through journal publications (Dasgupta and David, 1994; Stern, 2004). It is thus surprising that companies, given their short-term horizon and profit-driven orientation, invest significant amount of resources in science.[1]

Research in innovation has shown that investment in science leads to increases in performance. There is substantial evidence that undertaking corporate scientific research is positively linked to inventive output (Gibbons and Johnston, 1974; Gambardella, 1992; Narin, Hamilton and Olivastro, 1997; Cockburn and Henderson, 1998; Gittelman and Kogut, 2003) and firm performance (e.g., Griliches, 1985; Belenzon and Patacconi, 2014; Simeth and Cincera, 2016).[2]

The key mechanism behind this relationship is that corporations relying on science are able to create more valuable inventions (Murray and Stern, 2007). Thus, investing in science serves both as a direct input to invention (Arora et al., 2017) and as a channel to develop scientific absorptive capacity, which in turn allows the corporation to benefit from scientific discovery, more in general (Rosenberg, 1990; Cockburn and Henderson, 1998; Stern, 2004).

[1] In 2015, US corporations invested about $22 billions in basic research, which corresponds to about one quarter of the total science performed in the US (Arora et al., 2018). In 2018, Huawei, the Chinese technology giant, forecasted to dedicate about 20-30% of its $15 billions research budget to basic research (https://www.reuters.com/article/us-huawei-r-d/chinas-huawei-to-raise-annual-rd-budget-to-at-least-15-billion-idUSKBN1KG169).
[2] Although there is some evidence that US corporations invest less in science and the value of corporate science has declined in recent decades (Arora et al., 2018).

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While the relationship between science and invention and the role of science in fostering absorptive capacity have received much attention in the innovation literature (e.g. Fleming and Sorenson, 2004), we know little about how the organization of science within a corporation affects both its ability to use it as a direct input to invention and to build scientific absorptive capacity. The current paper addresses this research question. Specifically, we shall focus on the way firms internally organize their scientific and inventive activities; whether these activities are partitioned in distinct business units or they are collocated in a single business unit.

This is a research question of first order importance for innovative firms. For example, DuPont's experimental laboratory for multiple fields, which was organized as a separate scientific center, led to scientific breakthroughs that also generated commercial success, such as the discoveries of nylon, Teflon and Kevlar (Hounshell and Smith, 1986). Davisson's Nobel prize winning works on electron diffraction in Bell Labs and Irving Langmuir's Nobel Prize winning work on high vacuum in General Electric laboratories are examples of separate and scientifically driven, siloed centers of corporate research that generated important innovations (Maclaurin, 1953). In 2014, DuPont considered whether to split its biological and chemical R&D efforts into different units, in order to improve their scientific output. Some investors advocated for more focused entities as they did not see performance benefits from an integrated structure, while innovation executives at the company suggested that a split could erase benefits from combined R&D activities. More recently, before their merger with Dow, DuPont carried out a large-scale reorganization of their "existing Central Research and Development operating model to assess and seed new, transformational science-based ventures". Indeed, the move is a part of a trend of "evolving away from the exploratory research for which it is best known and toward science that addresses perceived needs of businesses". These examples indicate that the

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decision on how to organize science and invention is a non-trivial undertaking even for the most innovative companies.

To address our research question, we develop a theoretical framework that exploits the differences between science and invention as knowledge production systems. While scientists have greater discretion in choosing research projects and are typically rewarded based on establishing intellectual priority through journal publications (Dasgupta and David, 1994; Stern, 2004), inventors work on more targeted projects, which produce more appropriable returns. Scientists have a taste for science and are willing to trade monetary compensation for the possibility to work in a science-like environment (Stern, 2004; Rosenberg, 1990). Thus, organizing scientific research into a separate unit allows corporations to attract better scientists and provide them with stronger explicit and implicit incentives. Corporate scientific activity is more likely to be impactful within the scientific community, but at the same time less applicable to corporate invention.

On the other hand, by placing science and invention under the same corporate authority and possibly at close physical distance allows for greater interactions and knowledge exchanges between the two activities. In particular, inventors are more likely to learn from scientists. This implies that inventions become more scientific by integrating more scientific findings (Narin et al., 1997) and inventors are more likely to develop a generic capability to absorb and use science in downstream innovative activities (Cohen and Levinthal, 1990).

In this paper, we document empirically the existence of a tradeoff between pursuing stronger, but less applied science and having more science-based inventions and greater scientific absorptive capacity. To do so, we develop systematic data on the scientific and inventive activities of European corporate groups. Corporate groups are comprised of at least two legally

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independent business firms tied together via ownership linkages (Belenzon and Berkovitz, 2010). A corporate group has a controlling headquarter and separately incorporated business units that are controlled by the majority shareholders of the corporate group. Furthermore, earnings of incorporated business units are not consolidated at the group level, and business units also retain the ownership of their intellectual property. Finally, incorporated business units have large decision-making power in terms of the projects they pursue (Belenzon, Berkovitz, and Bolton, 2009). These features of business units make it an interesting context to explore the costs and benefits of integrating and separating science and invention within business groups.

Our sample is based on European business groups that during the period 2000-2007 were actively engaged in both science and invention. In our baseline analysis, we include 1816 business units belonging to 235 business groups.[3] We study collocation of science and invention within a given business unit. We measure science and invention through publications in scientific journals from the Web of Science, and granted patents at United States Patent and Trademark Office (USPTO), respectively. A key empirical challenge is to allocate publications and patents to business units. We do this by exploiting information in publication and patent documents to associate them to business units using addresses and author-inventor affiliations. We find a total of 100417 patents and 63437 publications belonging to these business units during the period under study.

Our results show that business units that perform both science and invention develop inventions with stronger scientific basis. Further we show that this happens not only because invention is

[3] We started from the entire population of public or private, incorporated European business units belonging to corporate groups with known address information. After assigning patents and publications to these business units, we selected only those business units belonging to business groups with at least 3 patents and 3 publications during the study period and for which we had information about total assets.

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organizationally and physically close to science, but also because collocation of science and invention helps a unit's inventors to develop scientific absorptive capacity, which allows them to draw on external science as well. Finally, we also find that scientific publications produced in business units that perform both science and invention have less scientific impact and are instead more likely to be cited by patents. We interpret these findings as evidence that science becomes more applied when collocated with invention.

The paper makes several contributions to extant literature on innovation. First, we point to an understudied aspect of the innovation process: While there is a lively debate about the importance of science for innovation and financial performance, little is known about how this relationship depends on the organization of science within corporations. We show indeed that the organization decision of scientific and inventive activities is an important factor affecting the outcomes of the innovation process. Second, we contribute to research on absorptive capacity by showing that choices about the organization of the science and invention also affect a unit's ability to identify and absorb extramural scientific knowledge. This responds to recent calls for a better understanding of the microfoundations of absorptive capacity (e.g. Lewin, Massini and Peeters, 2011). Finally, we also make an empirical contribution by offering the first systemic effort, to our knowledge, to develop business unit level data on science and invention activities of corporate groups in Europe.

The remainder of the paper is organized as follows: In the next section we build our theoretical framework for the organization decision of firms on scientific and inventive activities. In section 3, we describe our data sources and our steps of database construction. Section 4 presents our baseline regressions using a panel at the business unit-year level of analysis, while section 5 provides a battery of robustness checks. The ensuing discussion section concludes the paper. We present some of the challenges associated with our data work in the appendix.

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Theoretical Framework

The literature has advanced different reasons for why companies engage in in-house scientific activities. These reasons can be broadly grouped in two main buckets. First, science is often a direct input into innovation evident from the many inventions that would not have been possible without the underlying scientific knowledge (Rosenberg, 1990; Narin, Hamilton and Olivastro, 1997). Science fuels invention by narrowing the scope of search (Fabrizio, 2009), by facilitating more targeted experimentation (Rosenberg, 1974), decreasing search costs (Nelson, 1962; Evenson and Kislev, 1976) and focusing inventive activities (Kline and Rosenberg, 1986). Finally, scientific research projects generate important "non-findings" and discard explanatory mechanisms, thereby leading to faster outcomes in the delivery of products and processes (David, Mowery, Steinmueller, 1992).

Second, investments in science allow companies to identify and absorb new knowledge from the outside (Cohen and Levinthal, 1989; 1990). As most of the scientific research is conducted within university communities, firms require in-house investments in science to "plug in" to networks of university scientists (Cockburn and Henderson, 1998), which requires employing scientists doing cutting edge research in their field. An implication of this is that firms can preempt valuable resources and establish advantages by attracting top researchers (Rosenberg, 1990). As scientists have a "taste for scientific work", firms with scientific activities are able to attract high skilled workers that can generate breakthrough findings (Stern, 2004).

Ultimately, by investing in science firms increase the productivity of their inventors. There is indeed evidence that science-based inventions are more valuable (Arora et al., 2018; Murray and Stern, 2007).

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However, less is known about how the organization of science and invention within a corporate group affects the inventive activity, the development of scientific absorptive capacity and the type of science that is undertaken. Below, we will advance hypotheses on these relationships.

Collocation of science and invention within the same business unit puts both activities under the same organizational authority and under close physical proximity. In turn, this implies that scientists and investors are more likely to develop common skills, and share goals and incentives (Rosenberg, 1990; Pavitt, 1991; Szulanski, 1996), and are exposed to greater opportunities of knowledge exchange and learning across groups (Alcacer and Chung, 2007; Audretsch and Feldman, 1996).

A first implication of collocation is that the attention of scientific activities is directed toward more applicable ends. Despite the fact that science introduces new opportunities for invention, there are lags in the application of scientific findings in invention, as recent scientific findings may take time to be applied to practical ends (Klevorick et al., 1995). For instance, the scientific knowledge laying out the ground work for the transistors was available for 15 years before the inventors tapped into it (Nelson, 1962). Collocation, by forcing scientists and inventors, to share common goals and incentives reduces the opportunities to develop science that is too distant from applicable ends. Indeed, there is some evidence that science is influenced by industry. For instance, Hottenrot and Lawson (2014) show that a higher share of industry funding in a university research budget the more likely that its science is to source ideas from the private sector.

Second, collocation helps develop a "common language" that allows scientists to understand inventors, and inventors to understand scientists (Szulanski, 1996). This common understanding leads to focus on scientific findings that are more applicable in invention, and at

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the same time, invention that builds directly on a scientific basis. Indeed, it has been argued that inventive activities can also lead to scientific advances in the industry, rather than only science feeding new inputs into invention (Pavitt, 1996; Breschi, Lissoni and Montobbio, 2007). Collocation makes this feedback loops across the innovative value chain more likely (Kline and Rosenberg, 1986; Rosenberg, 1990). Scientists can learn directly from inventors and inventors can learn from scientists. For instance, IBM's Watson Laboratory pooled the research and development resources together by increasing the number of joint programs from 1 to 19 during the 1981-1989 period. Through these joint programs, IBM was able to speed up the introduction of new technologies and shorten product cycles (Gomory, 1989).[4]

Putting together these arguments we can formulate the following two hypotheses:

> **Hypothesis 1.a.** *Business units that carry out both scientific and inventive activities have more science-based inventions.*
>
> **Hypothesis 1.b.** *Business units that carry out both scientific and inventive activities develop more applied science.*

Hypothesis 1.a. states that collocation is associated with inventions that are more science-based. The mechanism we have discussed is that organizational and physical proximity makes inventors more likely to use the ideas of the scientists and scientists more likely to develop science that can be used by the inventors.

The collocation of scientific and inventive activities can help inventors to tap also into external science by developing scientific absorptive capacity at the business unit level (Cohen and

[4] The proximity of science and inventive activities in IBM laboratories has allowed for interactions that led mathematicians to provide speed improvements to calculations about electrical circuits, which in turn led to the development of breakthrough events in scientific knowledge, such as the devise of the asymptotic theory of integer programming (Gomory, 1987).

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Levinthal, 1989). This scientific absorptive capacity allows firms/units to keep abreast of the findings in scientific research and in turn to undertake more effective inventive activities. However, to reap the benefits of investment in science, "…it is not enough simply to hire world class scientists, allow them to do fundamental research and promote them on the basis of their standing in their field" (Cockburn and Henderson, 1998: 163). The key challenge is that inventors collaborate closely with scientists being the former those who develop the capability to understand, absorb and integrate science in their inventions. Reading the journals and attending scientific conferences may prove insufficient if inventors are not supported in their effort by scientists. There is evidence showing that inventors develop new skills through interactions with scientists (Pavitt, 1991).

Collocation, by creating organizational and physical proximity, enhances the opportunities of interactions and collaborations between scientists and inventors. Indeed, when science and invention are collocated in the same business unit, it is easier to provide incentives for knowledge sharing and transfer (Minbaeva et al., 2003), make use of the knowledge inventors absorb (Baldwin et al., 1991), and develop a culture of asking for solutions and help with problem solving (Hargadon and Sutton, 1997). Ultimately, collocation helps develop those routines that are crucial for understanding the microfoundations of absorptive capacity (Lewin et al., 2011). Thus, only by deliberately engaging in scientific activities, business units can build up higher order ability to identify, assimilate and exploit new scientific knowledge from outside of the unit/company (Cohen and Levinthal, 1989).

We conclude that by collocating science and invention activities at the business unit level, corporate groups are more likely to develop scientific absorptive capacity. The empirical implication is that, to the extent that a unit develops the ability to understand, absorb and utilize scientific knowledge, there is no clear prediction on whether inventive activities should use

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internally generated science versus science originating from outside the unit/firm's boundaries. We therefore test the proposed mechanism by investigating the extent to which business units resort to "external" science.

> **Hypothesis 2. (Scientific absorptive capacity)** *Business units that carry out both scientific and inventive activities are more likely to develop inventions that are based on extramural science.*

An important dimension of the choice on the organization of scientific and inventive activities is the incentive side of innovative labor (Aghion and Tirole, 1994). Since they have their own financial accounts, incorporated business units can craft contracts that are better suited for their main activities. Scientists have an ambition to develop novel findings and achieve recognition by the scientific communities in their fields of specialization through journal publications (Godin, 1996; Sauermann and Stephan, 2013). This often requires a long-term perspective. As such, incentive schemes should account for the possibility of early failures and rewards for long-term success, for instance, through a combination of stock options with long vesting periods, option repricing, golden parachutes, and entrenchment (Manso, 2011).

In contrast, invention is carried out towards commercial ends, with the goal of generating novel products and services that conform to the needs of customers in the marketplace. As such, disclosure of findings to competitors is typically avoided through either secrecy or other protection mechanisms (Dasgupta and David, 1994). By separating the scientific activities and inventive activities into two business units, business unit managers can align the incentives of their employees with the activities of the business unit more easily.

Separating scientists in a specialized business unit not only makes it easier to provide them with the right extrinsic incentives, but it also favors intrinsic motivation. Scientists like to be with scientists in a university-like environment where they can extend further their academic agenda

Tesi di dottorato "Essays on Corporate Science and Technological Change"
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in an open and cooperative way (Dasgupta and David, 1994). Evidence shows that scientists are willing to trade part of their salary for working in an environment that is more suitable for scientific enquire (Stern, 2004). Such non-pecuniary motives of industrial scientists have a strong effect also on the outcome of innovation activity (Sauermann and Cohen, 2010). Moreover, managers of incorporated business units can motivate scientists by conferring them decision rights that allow scientists to better pursue their own goals (Gambardella, Panico, and Valentini, 2015). Evidence indicates that such autonomy is indeed important for scientists, as they can use publishing as a substitute for social networks to diffuse the knowledge they produce (Sorenson and Singh, 2007).

While separating scientists in a specialized business unit might increase their scientific effort because of better incentives and stronger intrinsic motivation, it can also act as a means to attract better scientists. To the extent that the taste for science is heterogeneously distributed among scientists (Stern, 2004), those who are keener to develop scientific breakthroughs and become prominent within the scientific community perform especially better in a work environment that allows for intellectual challenge, and independence **(**Sauermann and Cohen, 2010**)**. Insofar the taste of science is correlated with talent (Stern, 2004), then collocation of science and invention might end up attracting less talented scientists or those with a more applied research agenda.

Finally, a similar logic applies to top-level decision makers of a corporate group reviewing performances of business units. Top-level decision makers can extend contract offers to managers that show a proven track record that might be conducive to long term rewards and short-term failures. Furthermore, top-level decision makers can bring in managers that have talents specific to the activity carried out by the business unit (i.e. scientific activities). There is qualitative evidence indicating the different functions and performance goals required of

Tesi di dottorato "Essays on Corporate Science and Technological Change"
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managers of scientific activities and managers of inventive activities (Chiesa and Frattini, 2007). Instead of dealing with two different activities, carried out by people with different backgrounds and motivations, specialized business units can align the management expertise with the principal activity of the business unit, thereby leading to better quality in the scientific activities.

Putting together these arguments, we can state:

> **Hypothesis 3.** *Business units that carry out both scientific and inventive activities are less likely to develop science that is impactful within the scientific community.*

A short declaimer is due now. As we have argued above, collocation not only helps inventors to develop more science-based inventions, but it can foster feedback loops across the innovation value chain more in general (Kline and Rosenberg, 1986; Rosenberg, 1990). Thus, inventive activities can also lead to scientific advances (Pavitt, 1996; Breschi, Lissoni and Montobbio, 2007). Science can be inspired by inventive activities. This synergistic relationship between invention and science that is likely to be strengthened when the two activities are collocated, might be sufficiently strong to reverse the negative relationship between collocation and quality of corporate science that we have stated in H3. Ultimately, it is an empirical question to assess which force dominates.

Data Construction and Empirical Setting

We investigate our theory in the context of European business groups. Business groups have several important features that are pertinent to our data collection and make them an ideal test bed. First, majority shareholders of a business group own controlling stakes in legally independent business units, and as such, business units are not necessarily wholly-owned

Tesi di dottorato "Essays on Corporate Science and Technological Change"
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subsidiaries. Second, business units have unconsolidated accounts that reflect financial information specific to the unit. Third, as they are legally independent entities, business units have considerable decision-making rights on the direction of their research activities. Fourth, European business units of corporate groups can retain their intellectual property because the European Corporate Group Law restricts reassignment of intellectual property to different affiliates within the same corporate group (Belenzon, Berkovitz, and Bolton, 2009). In order to test our hypotheses, we need to develop systematic data on the science and invention activities of business units that are part of a corporate group, as well as their ability to utilize the science produced by these business units.

Following extant literature (Arora et al. 2015; 2017; 2018; Bikard, 2018; Callaert et al., 2014; Marx and Fuegi, 2019; Roach and Cohen, 2013), we use scientific publications, granted corporate patents and non-patent literature (NPL) citations used in patent applications to operationalize our theoretical constructs of scientific activities of business units, inventive activities of business units and the use of science in inventions by business units, respectively. Using patents as a measure of inventive activities has well-known drawbacks. For instance, not all inventive activities are patented, industries differ in their propensity to patent inventions, industry assignments of patents may not be completely precise and patents differ in their economic value (Pavitt, 1988; Griliches, 1998). However, patents also provide publicly available and objective measures of inventive activities. Namely, patents undergo an evaluation process involving external examiners, they are used across a broad range of technology classes and they contain specific information on the technology and the inventor, including the assignee name (Pavitt, 1985; Griliches, 1998). Similarly, corporate scientific publications provide a publicly available measure of the corporate scientific activities. Indeed, corporate scientists publish intensively, similar to academic scientists (Murray and Stern, 2007; Sauermann and

Tesi di dottorato "Essays on Corporate Science and Technological Change"
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Stephan, 2013). However, firms pay significantly more attention to publications “made in industry” compared to publications “made in academia”, because they perceive publications from industry to be more relevant for their ends (Bikard, 2018). Only a small fraction of publications is cited in patent documents, and not all fields of scientific knowledge receive the same attention from patents (Ahmadpoor and Jones, 2017). Despite some drawbacks, we follow the earlier literature using corporate scientific publications (e.g. Gibbons and Johnson 1974), while we also use patent citations to non-patent documents (Narin, Hamilton, and Olivastro 1997; Arora, Belenzon, and Patacconi, 2018) to measure the use of science in inventive activities. Patents citations to academic papers are better measures of actual knowledge flows than citations to other patents (Roach and Cohen, 2013) because citations to other patents are also added by patent examiners (Alcácer, Gittelman, and Sampat, 2009). Finally, we use the number of citations made by other scientific publications, to measure the quality of scientific publications.

Our main empirical challenge is to assign publications and patent records to European business units of corporate groups. The key issue is that there is no unique business unit identifier that would allow us to unambiguously link publications and patents to business units within corporations. This association has been obtained through a careful matching process. We describe all the details of our database construction strategy in Appendix 1. Here we briefly outline the main steps:

- Matching scientific publications and patents to European Business Units

For scientific publications, we use data from the Web of Science database that covers scientific articles published in a comprehensive set of journals. For patents, we use data from the USPTO. We start our search with all business units located in Europe for which we have ownership and financial information and that are owned by European corporate groups. We obtain ownership

Tesi di dottorato "Essays on Corporate Science and Technological Change"
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and financial data from Orbis by Bureau Van Dijk (henceforth, BvD). We look for exact and fuzzy matches between the name of the business units and the affiliation of the scientist in the publications or the assignee name in the patents, and clean the false positives in the resulting set of matched pairs. One of the key problems is that many business units of the same corporate group display the same name. For instance, in the corporate group of Unicredit, an Italian multinational company of the banking industry, there are 56 business units with the name "Unicredit". Thus, the matching process above would not allow us to allocate publications by scientists affiliated to Unicredit (or inventions assigned to Unicredit) to the individual business units. In order to link publications and patents to business units within corporations we perform a further round of matching by using address information contained in the publications and in the patent documents, and compare them to the address information of business units. For patent assignees, we have city level information, whereas with address fields of publications, we have information about the street address and zip code of the authors in many cases. While discerning the business unit, we use the available information in the following order: Street address and number, postal code, city, region, country. After an initial round of matching based on exact information, we use proximity scores to check the edit distance between the company address fields and publication/patent addresses.

- Matching Non-Patent Literature Citations to Web of Science Records

Finally, we use the non-patent-literature (NPL) citations listed on the first page of patent applications filed at the USPTO. Patent documents contain detailed information on citations to other patents and to non-patent documents. We use the latter as our main dependent variable to test our theoretical conjectures on the use of corporate science in inventive activities. Since patents and publications are assigned to business units based on address information, as described above, this information allows us to discern the location of the science that is used in

Tesi di dottorato "Essays on Corporate Science and Technological Change"
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patent documents, and whether such scientific knowledge is sourced from within the business unit, other business units of the same group or outside of the business group, which is crucial for testing our hypothesis on scientific absorptive capacity.

Sample, Analysis and Results

We run our baseline regressions at the business unit-year level of analysis. The business unit is the organizational and physical locus where scientific and inventive activities are conducted and where the decision to collocate or separate science and invention becomes pertinent. This unit of analysis is also fully consistent with our theoretical hypotheses. Nevertheless, in the following section, we provide some robustness tests at the corporate group-year and the publication-patent dyad levels of analysis. In our baseline regressions below, we exploit the time variation of the within-unit changes from collocation to specialization and the across-unit variation between business units with collocated versus specialized scientific and inventive activities.

Our sample covers the period 2000-2007 for which we have complete information about ownership, publications, patents and citations of European business units. We restrict attention to corporate groups with considerable scientific and inventive activities, given our goal to investigate how the organization of science and invention in corporations affects their scientific and inventive outputs. Therefore, we focus on groups with at least 3 publications and 3 patents during the period of 2000-2007. Variations of the inclusion threshold provide qualitatively similar results. This gives us a total of 1816 European business units belonging to 235 corporate groups. The business units of our sample have on average 1.3 publications in scientific journals per year that receive slightly less than 7 scientific citations in total. They display on average 3.2 granted patents per year. Their average total assets are $60.5 millions. However, there is huge

Tesi di dottorato "Essays on Corporate Science and Technological Change"
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heterogeneity across business units. Below, we report descriptive statistics, variable descriptions and pairwise correlations for the variables used in our baseline regressions.

Our main independent variable is whether scientific and inventive activities are collocated at the business unit level or not. We measure it through a dummy variable (Collocation) that takes the value of 1 if the two activities are collocated and 0 otherwise. We consider that scientific and inventive activities are collocated if a given business unit has at least one patent and one publication in the years t, t-1, t-2 and t-3. Collocation is not common in our sample. Only 9% of business unit-year observations display collocation of scientific and inventive activities.

To test our hypotheses we use different dependent variables. When we investigate the use of science in invention (H1a and H2), we employ as dependent variables the numbers of NPL citations contained in the granted patents filed by a given business unit at time t and made to scientific publications of the same business unit (Use of BU Science), other business units of the same corporate group (Use of Group Science), and other corporations (Use of External Corporate Science), respectively. When we investigate the quality of the scientific output produced by a business unit (H1b and H3), we employ as dependent variables the citations that publications of the business unit in a given year receive from patents (Applied Science) and other scientific publications (Scientific Citations), respectively.

[Insert Table 1 and 2 about here]

We estimate the following linear regression equation for the different dependent variables that we explained above:

$$Y_{it} = (Collocation_{it}) \times \alpha_c + Controls_{it} \times \alpha_x + \beta_t + \beta_{group} + \beta_{country} + \varepsilon_{it}$$

where i represents each of the 1816 business units of our sample, t is years 2000-2007, Collocation is the dummy variable explained above, Controls is a set of control variables, β_t are year dummies, β_{group} are group dummies, and $\beta_{country}$ are country dummies. We control for the

Tesi di dottorato "Essays on Corporate Science and Technological Change"
di DALAY HAKKI DOGAN
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total assets of a business unit because there are likely scale effects both in the production of science and in the use of science in invention.[5] As we measure the use of science in invention through NPL citations in patents, business units that patent more will mechanically have a larger number of NPL citations. We therefore control for the total number of patents in all regressions that test for the use of science in invention. Similarly, because the number of scientific citations and patent citations to scientific publications (our variables Scientific Citations and Applied Science, respectively) are also mechanically increasing in the number of publications, we control for the total number of publications by a given business unit in a given year in those regressions.[6] The year dummies control for potential variation across years in the macro environment that might affect both scientific production and inventive activities, while group dummies capture time invariant characteristics of the business group. We also cluster standard errors at the business unit level as unobserved factors in the outcome variables we use in our analysis could be correlated at the business unit level.

Overall, we have a balanced panel to run our analyses, where we observe each of our 1816 business units across the 8 years of our sample period. Our results indicate that collocation of science and invention at the business unit is associated with greater use of science in inventions (Model 1), providing support to H1a. However, this comes at the cost of science that has a smaller impact in the scientific community (Model 2) and is more applied (Model 3), although this latter coefficient is not statistically significant. These findings are consistent with H1a and H3. We also find evidence indicating that the collocation of science and inventive activities

[5] In alternative regressions, we have used the business unit's total cash flow in a given year, also together with total assets, with unchanged coefficients on the Collocation dummy.
[6] An alternative approach would be to scale the number of NPL citations by the number of patents in a given year and the number of patent citations and scientific citations by the number of publications in a given year. These regressions produce qualitatively similar results and are available upon request.

Tesi di dottorato "Essays on Corporate Science and Technological Change"
di DALAY HAKKI DOGAN
discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2020
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leads to an increase in the use of external science in invention. Indeed, not only patents refer more often to scientific publications of other business units of the same corporate group (Model 4), but also rely more often on scientific publications developed by other companies (Model 5). Together these last two findings provide evidence that collocation of science and invention is a mechanism through which firms develop scientific absorptive capacity that allows them to tap more effectively into their own and extramural science.

One of the drawbacks of the balanced panel approach is that it displays a large number of zeros both in the dependent variables and in the Collocation dummy. This might raise some concerns about the fact that we run our analysis on business units that neither perform science nor invent. Indeed, because of the large number of zeros our dependent variables have small means and high standard deviations. One consequence is that the magnitude of the effect is difficult to interpret because the sample mean is not representative of the behavior of business units engaged in scientific and inventive activities. To alleviate this concern, we run our regressions by conditioning the sample to those observations that display positive patenting activity or positive publishing activity in a given year. More precisely, we study the use of science in inventive activities only for those business unit-year observations that have non-zero patents in a given year. We study the effect of collocation on scientific activities only for those business unit-year observations that have non-zero publications in a given year. These generate two unbalanced panels of respectively 2561 and 2703 observations. Descriptive statistics for these samples are reported in Table 4A and 4B.

Overall, results are qualitatively similar. See Table 5. Collocation boosts significantly the use of science in invention and is positively associated with greater use of science from external sources both within the business group and outside the group, consistent with the notion that

Tesi di dottorato "Essays on Corporate Science and Technological Change"
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discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2020
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collocation helps develop scientific absorptive capacity. The variables that capture the impact of collocation in internal scientific activities are now both significant although only at the 10% level. Thus, there is some weak supporting evidence for our H3: by isolating scientists from inventors the corporation can make them more effective in producing high quality scientific outputs.

[Insert Table 4A, 4B and 5 about here.]

We use these latter regressions to quantify the magnitude of our coefficients. When the average business units of our sample switches collocation from zero to one, we observe an increment of citations to science produced by the business unit, science produced by other business units of the same group and by other groups of 0.6, 1.1 and 0.9, respectively. Compared to the average use of these different types of science of a given business unit, these numbers imply an increment of respectively 205%, 227%, and 56%. At the same time, we observe a decrease in scientific citations and an increase in patent citations to the science produced by the average business unit of respectively 27% and 56%. While these effects are small in absolute terms, their magnitude is economically significant.

Robustness Checks

We discuss here two main alternative specifications that allow us to capture different aspects of the relationships we develop in our hypotheses. First, since we know the unit-level owner of patents and publications, as well as the corporate structure of the business units, we aggregate our unit-level data to corporate group level, and repeat our analyses at that level. This has the advantage to conduct the analysis at the same level decisions about collocation are made, i.e. the business group. However, collocation occurs at the business unit, so to study it at the group level, we need to build a measure of the degree of collocation of the whole group. To do so, we construct for each business group and year a vector of the shares of patenting activity and a

Tesi di dottorato "Essays on Corporate Science and Technological Change"
di DALAY HAKKI DOGAN
discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2020
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Sono comunque fatti salvi i diritti dell'università Commerciale Luigi Bocconi di riproduzione per scopi di ricerca e didattici, con citazione della fonte.

vector of the shares of publishing activity of each of its business units. By multiplying these two vectors, we obtain our measure of collocation at the group-year level, where a value of 1 implies complete collocation (i.e. all patents and publications are concentrated in a single business unit of the corporate group in that year) and 0 implies full specialization (i.e. none of the business units engaged in publishing does also have patents).

At the group level, it is possible to look at the NPL citations that patents of the group make to its own scientific publications (Use of Group Science), and to scientific publications belonging to different corporate groups (Use of External Corporate Science). The other two dependent variables we used in our unit-year level of analysis, i.e. the total number of NPL citations received by publications of the business unit and the scientific citations received by the publications of the business unit, are aggregated in a straightforward manner at the corporate group level.

Descriptive statistics are reported in Table 6 and results in Table 7. Similar to the analysis at the business unit/year level, we use linear regressions with year and country dummies and we cluster the standard errors at the group level. The results indicate a negative effect of collocation on the scientific publications, and a positive and significant effect of collocation on the use of internal and external science, consistent with our previous findings.

In the second robustness check, we look at whether an NPL citation from a patent to a publication is more likely to occur if the patent and the publication originate from the same business unit. This unit of analysis allows us to provide further support for the importance of collocation in favoring knowledge exchanges between scientists and inventors. However, it cannot be used to test the hypotheses on the implications that collocation has on corporate science. Towards this end, we create a dataset comprised of the matrix multiplication of patents that make at least one NPL citation (N=9,932) and publications that receive at least one NPL

Tesi di dottorato "Essays on Corporate Science and Technological Change"
di DALAY HAKKI DOGAN
discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2020
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citation (N=12,026), thereby generating a dataset with 119,442,232 observations in it. A method commonly used in alliances literature is to look at the occurrence of an event (e.g. alliance formation, technology overlap between the parties) as a dyadic relationship between two sides of the transaction (Gimeno, 2004; Alcacer and Oxley, 2014). A strong assumption implicit in this analysis is that all patents with NPL citations to corporate science can cite all corporate publications that have received at least one NPL citation. Our main dependent variable "PatCitesPub" assumes a value of 1 if the focal patent has an NPL citation to the focal publication in a patent-publication dyad. Tables 8 and 9 report the descriptive statistics and pairwise correlations for the variables used in this level of analysis.

[Insert Tables 8 and 9 about here]

$$\Pr(\text{NPL Citation}) = (\text{Collocated Pats\&Pubs}) \times \beta_i + \text{Controls} + \sum_i$$

Here, we use three variables to explain the instance of an NPL citation. We use dummy variables that takes the value of 1 when the citing patent and the cited publication are from the same corporate group ("samegroup"), same business unit ("sameunit") and same industry ("samesic"). We also use time dummies for scientific articles' publication years and patent grant years.

In the first model, we regress the instance of an NPL citation on the samegroup, sameunit and samesic variables and use corporate group fixed effects. Our first finding is that the units with collocated patent and publication activities are more likely to generate NPL citations in their patents and this and that the positive and significant effect of the "sameunit" variable is stronger than that of the "samegroup" variable (Model 1). This effect is robust when we add fixed effects for publication ids and patent ids with high dimensional fixed effects (Guimaraes and Portugal,

Tesi di dottorato "Essays on Corporate Science and Technological Change"
di DALAY HAKKI DOGAN
discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2020
La tesi è tutelata dalla normativa sul diritto d'autore (Legge 22 aprile 1941, n.633 e successive integrazioni e modifiche).
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2009) in Model 2.[7] Due to the large scale of the multiplied matrix, adding new variables presents challenges on memory and processing power requirements, but we interpret these findings consistent with our theoretical conjectures. The persistent effect of the "sameunit" variable indicates an effect of collocation on the use of science that remains even after accounting for collocation at the group level. It implies that beyond the effect of collocation in the same business unit, being the same group with scientific publications, has a positive effect on the likelihood of citing NPL in patent documents. In Model 1, being in the same unit translates into a focal publication being about twice as likely to be cited by a patent if the patent and the publication originate from the same unit. As this main independent variable is a 0-1 coded variable, patenting originating from units that have publications and patents together, are more than twice as likely to cite a publication in the patent document, compared to units of the same corporate group active in the same industry. The economic significance of the main effect persists at comparable levels throughout all the specifications where the dependent variable is the number of NPL citations.

Discussion

The results we present in this paper indicate a trade-off between the ability to use science and the production of scientific output in large corporations engaged in both scientific and inventive activities. Our evidence shows that by collocating scientific research with inventive activities in integrated units, large corporations are able to create inventions with a stronger scientific emphasis. Units that have both patenting and publishing activity are better positioned to cross-

[7] In unreported regressions we confirm that these effects remain virtually the same when we use year controls and fixed effects for patent classes and when we use sameunit variable without samegroup variable in the regression, and when we add size controls for the sales of the patenting units and publishing units. We also get similar results when we don't use corporate group fixed effects and samesic variable.

Tesi di dottorato "Essays on Corporate Science and Technological Change"
di DALAY HAKKI DOGAN
discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2020
La tesi è tutelata dalla normativa sul diritto d'autore (Legge 22 aprile 1941, n.633 e successive integrazioni e modifiche).
Sono comunque fatti salvi i diritti dell'università Commerciale Luigi Bocconi di riproduzione per scopi di ricerca e didattici, con citazione della fonte.

pollinate ideas and benefit from the efforts on both sides of the innovative activity. But the ability to make better use of science in invention comes at a cost. As a business unit tries to do scientific and inventive activities together in the same unit, their scientific research suffers in terms of quality. Business units with integrated inventive and scientific activities produce lower quality scientific output compared to business units focusing only on scientific activities. In other words, firms have to give up on the quality of science, when they want to make better use of science in their inventions. Furthermore, we show that the mechanism underlying our findings on the positive effect of collocation on the use of science is one based on capability development of firms, rather than additional inputs that are available due to sheer proximity of scientists and inventors. Indeed, collocation of scientific and inventive activities leads to the development of scientific absorptive capacity that allows firms to navigate external knowledge sources, rather than only opting for the closest scientific knowledge available.

An essential question that has arisen in the literature on innovation strategy is the declining role of science in corporations in the US, despite the clear importance of science in the industry (Arora et al., 2018). Firms' inability to use the science they produce emerges as a reason as to why companies withdraw from scientific efforts (Arora et al. 2017). Notwithstanding, the ability to access knowledge at the frontier of a scientific field is crucial for the creation of new ideas, but accessing this knowledge requires skills that are difficult to build in the absence of leading scientists of a field who themselves produce frontier knowledge (Iaria, Schwarz, and Waldinger, 2018). At the same time, processing and transforming knowledge into usable form is the key for the development of new technologies (Weitzman, 1998). Our evidence builds on this paradigm and indicates an important trade-off for large corporations: So as to make use of science in their inventions, firms have to give up on producing high quality research. In other

Tesi di dottorato "Essays on Corporate Science and Technological Change"
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words, to produce higher quality research, firms need to distance their scientific output from their inventive activity.

The results of this study carry several implications for strategy. The literature on the organization of research and development indicates a move away from scientific research in corporations. First, it is possible that research efforts in corporations is failing because scientific activities should be carried out by other, more specialized institutions that may have an advantage in carrying out research, such as universities or small firms. Another explanation may be that the centralized research that separates science from invention is failing. If the latter is the case, maybe there is room for research in large corporations as long as it is decentralized and collocated with inventive activities. Our paper informs this key strategic decision.

Our paper has several limitations. Beyond the limitations we discussed while describing the data construction process in the data section, we also remind the reader that we bring data from multiple sources. The main problem we have faced so far is the unavailability of the financial information for the sample firms before 2000.

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Table 1. Descriptive Statistics and Variables Used in Unit-Year Level of Analysis

Variable Name	Variable Description	Observations	Mean	St Dev	Min	Max
Collocation	Dummy equal to 1 if a business unit has patents AND publications in years t, t-1, t-2, t-3	14,528	0.08962	0.285647	0	1
Total Assets	Log of total assets of a business unit in year t	14,528	17.918	3.941966	0	27.8798
Publications	Number of scientific publications of a business unit in year t	14,528	1.27774	9.054261	0	296
Patents	Number of patents of a business unit in year t	14,528	3.223155	36.22601	0	1307
Scientific Citations	Number of scientific citations received by the publications of a business unit in year t	14,528	6.832186	69.25019	0	3646
Use of BU Science	Number of citations made by the patent of a business unit in year t to publications of the same business unit	14,528	0.053965	0.8521	0	25
Applied Science	Number of patent citations received by the publications of a business unit in year t	14,528	0.6038	8.491199	0	383
Use of Group Science	Number of citations made by the patents of a business unit in year t to publications of other business units of the same group	14,528	0.086247	1.255947	0	62
Use of External Science	Number of citations made by the patent of a business unit in year t to external corporate publications	14,528	0.282902	2.631249	0	74

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Table 2. Pearson Correlations for the Variables Used in the Unit-Year Level of Analysis

	Collocation	Total Assets	Publications	Patents	Scientific Citations	Use of BU Science	Applied Science	Use of Group Science	Use of External Corporate Science
Collocation	1								
Total Assets	0.18	1							
Publications	0.16	0.14	1						
Patents	0.12	0.11	0.18	1					
Scientific Citations	0.1	0.09	0.82	0.1	1				
Use of BU Science	0.2	0.08	0.4	0.36	0.27	1			
Applied Science	0.11	0.07	0.67	0.14	0.65	0.36	1		
Use of Group Science	0.2	0.08	0.34	0.35	0.24	0.78	0.27	1	
Use of External Corporate Science	0.18	0.11	0.25	0.75	0.16	0.41	0.18	0.47	1

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Table 3. Effect of collocation on scientific and inventive activities: unit-year level of analysis

Variables	(1) Use of BU Science	(2) Scientific Citations	(3) Applied Science	(4) Use of Group Science	(5) Use of External Corporate Science
Collocation	0.509***	-8.304***	0.468	0.798***	0.935***
	(0.134)	(2.975)	(0.512)	(0.217)	(0.242)
Total Assets	0.00313	-0.184*	-0.0406**	0.00555*	0.0114
	(0.00231)	(0.100)	(0.0172)	(0.00302)	(0.00956)
Patents	0.00844**			0.0123**	0.0534***
	(0.00404)			(0.00606)	(0.00788)
Publications		6.338***	0.623***		
		(0.471)	(0.0818)		
Year Dummies	YES	YES	YES	YES	YES
Group Dummies	YES	YES	YES	YES	YES
Country Dummies	YES	YES	YES	YES	YES
Observations	14,528	14,528	14,528	14,528	14,528
R-squared	0.213	0.684	0.475	0.200	0.606

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

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Table 4A. Descriptive Statistics and Variables Used in Unit-Year Level of Analysis (conditional on positive patenting in a given year)

Variable Name	Variable Description	Observations	Mean	St Dev	Min	Max
Collocation	Dummy equal to 1 if a business unit has patents AND publications in years t, t-1, t-2, t-3	2,564	0.350624	0.477259	0	1
Total Assets	Log of total assets of a business unit in year t	2,564	19.51447	3.41516	0	26.20335
Patents	Number of patents of a business unit in year t	2,564	18.26287	84.63707	1	1307
Use of BU Science	Number of citations made by the patent of a business unit in year t to publications of the same business unit	2,564	0.305772	2.009563	0	25
Use of Group Science	Number of citations made by the patents of a business unit in year t to publications of other business units of the same group	2,564	0.48869	2.957012	0	62
Use of External Science	Number of citations made by the patent of a business unit in year t to external corporate publications	2,564	1.602964	6.093043	0	74

Table 4B. Descriptive Statistics and Variables Used in Unit-Year Level of Analysis (conditional on positive publishing in a given year)

Variable Name	Variable Description	Observations	Mean	St Dev	Min	Max
Collocation	Dummy equal to 1 if a business unit has patents AND publications in years t, t-1, t-2, t-3	2,708	0.292836	0.455148	0	1
Total Assets	Log of total assets of a business unit in year t	2,708	19.29197	3.618716	0	27.65178
Publications	Number of scientific publications of a business unit in year t	2,708	6.854874	20.04234	1	296
Scientific Citations	Number of scientific citations received by the publications of a business unit in year t	2,708	36.65362	156.9773	0	3646
Applied Science	Number of patent citations received by the publications of a business unit in year t	2,708	3.239291	19.45209	0	383

Tesi di dottorato "Essays on Corporate Science and Technological Change"
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Table 5. Effect of collocation on scientific and inventive activities: unit-year level of analysis (conditional on positive patenting or publishing in a given year)

Variables	(1) Use of BU Science	(2) Scientific Publications	(3) Applied Science	(4) Use of Group Science	(5) Use of External Corporate Science
Collocation	0.626***	-9.848*	1.858*	1.112***	0.892***
	(0.136)	(5.163)	(0.951)	(0.276)	(0.311)
Total Assets	0.0250*	-0.882*	-0.112*	0.0418*	0.0514
	(0.0136)	(0.522)	(0.0680)	(0.0217)	(0.0528)
Patents	0.0100**			0.0146**	0.0523***
	(0.00408)			(0.00635)	(0.00791)
Publications		6.514***	0.603***		
		(0.440)	(0.0789)		
Year Dummies	YES	YES	YES	YES	YES
Group Dummies	YES	YES	YES	YES	YES
Country Dummies	YES	YES	YES	YES	YES
Observations	2,561	2,703	2,703	2,561	2,561
R-squared	0.443	0.705	0.519	0.397	0.691

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

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Table 6. Descriptive Statistics and Variables Used in Group-Year Level of Analysis

Variable Name	**Variable Description**	**Observations**	**Mean**	**St Dev**	**Min**	**Max**
Collocation	Uncentered correlation distance between the shares of publication and patenting activity of business units in a group at time t.	1,880	0.223337	0.382814	0	1
Total Assets	Log of total assets of a group in year t	1,880	21.46952	2.75559	10.16589	28.67264
Publications	Number of scientific publications of a group in year t	1,880	9.336702	27.74463	0	341
Patents	Number of patents of a group in year t	1,880	25.14362	102.231	0	1307
Scientific Citations	Number of scientific citations received by the publications of a group in year t	1,880	50.00691	209.6973	0	4044
Applied Science	Number of patent citations received by the publications of a group in year t	1,880	4.435106	26.37877	0	656
Use of Group Science	Number of citations made by the patents of a group to publications of the same group	1,880	0.632979	3.630393	0	82
Use of External Science	Number of citations made by the patents of a group in year t to external corporate publications	1,880	2.140426	7.469396	0	74

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Table 7. Effect of collocation on scientific and inventive activities: group-year level of analysis

	(1)	(2)	(3)	(4)
Variables	Scientific Publications	Use of Group Science	Use of External Corporate Science	Applied Science
Collocation	-18.85**	1.202***	1.463**	0.826
	(9.416)	(0.330)	(0.638)	(1.897)
Total Assets	-2.850***	0.110**	0.254***	-0.501**
	(0.936)	(0.0428)	(0.0876)	(0.221)
Patents		0.0119*	0.0518***	
		(0.00610)	(0.00864)	
Publications	6.269***			0.699***
	(0.413)			(0.114)
Year Dummies	YES	YES	YES	YES
Country Dummies	YES	YES	YES	YES
Observations	1,880	1,880	1,880	1,880
R-squared	0.692	0.162	0.553	0.535

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Table 8. Descriptive Statistics and Variables Used in Citation Level of Analysis

Variable Name	Variable Description	Observations	Mean	St Dev	Min	Max
PatCitesPub	Instance (0-1) of NPL citation from patent to publication	119,442,232	0.0001017	0.0100819	0	1
timescited	Number of scientific citations to the publciation	119,442,232	17.99534	47.35802	0	1715
sameunit	Instance (0-1) of patent and publication from the same business unit	119,442,232	0.0109701	0.1041624	0	1
samegroup	Instance (0-1) of patent and publication from the same corporate group	119,442,232	0.0181695	0.1335641	0	1
samesic	Instance (0-1) of patent and publication from the same 3 digit industry sic code	119,442,232	0.0866207	0.2812784	0	1
sales_pub	Sales of the unit of scientific publication	109,093,088	4.18e07	7.56e07	1.299	4.81e08
sales	Sales of the unit of patent	108,666,936	4.76e07	9.83e07	3.897	9.03e08

Table 9. Pearson Correlations Table for the variables used in the Citation Level of Analysis

	PatCitesPub	timescited	sameunit	samegroup	samesic	sales_pub	sales
PatCitesPub	1.0000						
timescited	0.0016	1.0000					
sameunit	0.0085	-0.0072	1.0000				
samegroup	0.0083	-0.0015	0.7742	1.0000			
samesic	0.0046	0.0201	0.3403	0.3055	1.0000		
sales_pub	0.0005	-0.0248	0.0643	0.0550	-0.0268	1.0000	
sales	-0.0006	0.0000	0.0431	0.0255	-0.0551	-0.0000	1.0000

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Table 10. Citation level of analysis. OLS regressions with patent-publication dyad.

	(1)	(2)
VARIABLES	PatCitesPub	PatCitesPub
sameunit	0.0004832***	0.0004999***
	(0.0000145)	(0.0000152)
samegroup	0.0003245***	0.0003213***
	(0.0000111)	(0.0000124)
samesic	0.0000566***	0.0000682***
	(3.73e-06)	(4.08e-06)
Constant	0.0000712	
	(0.0001121)	
Observations	117698462	119442232
R-squared	0.0001	0.0008

Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1
Model 1 includes corporate group fixed effects and controls for patent grant years and publication years
Model 2 includes both patent id and publication id fixed effects.

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APPENDIX A: DATA CONSTRUCTION STRATEGY

We follow four main steps to construct our data.

1. Matching scientific publications to European Business Units

We match data from the complete Web of Science database covering scientific articles published during 1980-2007 with ownership data from Orbis by Bureau Van Dijk (henceforth, BvD). Our sample includes all business units in Europe with ownership and financial information that are owned by European corporate groups.

We start by cleaning and standardizing company names and address fields of scientific publications. Then, we join publications data with company names, essentially to form a 162,841x14,388,204 large matrix, whereby we have 162841 incorporated European business unit names, and 14388204 publication records. We look for exact matches to company names within publication address/affiliation fields at this initial stage and drop the cases with none of the company names in our sample appearing in the publication addresses. Then, we clean the matched pairs based on the frequencies of company names. In this manual process, we filter generic names, and short company names and screen for company names comprised of a single word. At this stage, the resulting file contains all publication addresses that include our standardized company names (e.g. “ROCHE”, “BASF”, “BAYER”). The same name-publication matches appear as many times as the number of business units. For instance, at the end of this cleaning stage, we observe 56 duplicates for each publication with “UNICREDIT” appearing in its address field, as 56 of the business units have the same name in the corporate group of “UNICREDIT”. This step is followed by the second step below, to identify the owner of the publication at business unit level. This process gives us a total of 96997 publications belonging to 3819 European business units.

2. Matching patents to European Business Units

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We use ownership data from Orbis and match companies to the assignee information from the USPTO database. This initial step is similar to the first step with publications. We match company names from Orbis Bureau Van Dijk with the assignee fields of the granted patents. We look for exact and fuzzy matches and clean the false positives in the resulting set of matched pairs. Once we obtain the initial set of matches, we proceed to make business unit specific assignments. This process gives us 216530 patents belonging to 38506 European business units.

3. Assigning Publications and Patents to Business Units

This is the critical step in our data construction as our analysis relies on the assignments of the publications and patents to business units. In the ideal situation, BvD identifiers would unambiguously link publications and patents to business units within corporations. Since there is no such linkage, we have to rely on address-based string matching to make assignments to business units, thereby measuring our theoretical constructs properly. For patent assignees, we have city level information, whereas with address fields of publications, we have information about the street address and zip code of the authors in many cases. As our theoretical development hinges on the separation of legal entities, using address information and making these assignments at the business unit level is the only way to test our theory. While discerning the business unit, we use the available information in the following order: Street address and number, postal code, city, region, country. After an initial round of matching based on exact information, we use proximity scores [8] to check the distance between the company address fields and publication addresses.

In this step, we combine company information with annual address information on European business units from Orbis for the 2002-2011 period, which includes address, postal code, city,

[8] We employ metrics of vectorial decomposition as well as Jaro-Winkler and Levenshtein edit distances, along with adjusted metrics based on the length of the company address strings.

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region and country information for all the firms in our sample. We complement this data with address information for our full set of companies from the online database in March 2018. The address information is crucial to assign publications and patents to separate legal entities.

After the initial cleaning steps of 1 and 2 for publications and patents we described above, we add address information for companies to the full set of company-publication matches. We clean the address fields for punctuation marks and special characters similar to the procedure we employed for addresses of scientific publications. After switching to capital letters, we clean all special characters in all official European languages in these address fields and replace them with corresponding letters in the Latin alphabet. Our definition of a business unit relies on company name – address pairings, as we are interested in the separation or collocation of science and invention activities for separate legal entities. However, assigning publications to business units involves several challenges. Challenges arise from working with companies originating from countries with different local languages as well as the fact that company names can also appear in other institutions, research centers and private-public collaborations. Other challenges are common to any process involving merging data from multiple sources with different conventions.

In some cases, city names appeared in different ways for addresses of business units over time (e.g. WIEN, VIENNA; MILAN, MILANO; COLOGNE KOLN; BRUSSELS, BRUXELLES; FLORENCE, FIRENZE). Where possible, we reduced city fields to the longest common string (e.g. PARIS, MILAN, BRU). Some of these cases are city names in local languages, or they contain additional information from another field appearing in the same field (e.g. AMSTERDAM, AMSTERDAM ZUIDOOST; KLAGENFURT, KLAGENFURT AM WORTHERSEE, KLAGENFURT AM WOERTHERSEE; SALZBURG, BERGHEIM, BERGHEIM AM SALZBURG; NEWCASTLE, NEWCASTLE UPON TYNE). We kept such

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information in distinct information fields so as not to miss possible exact matches. In some cases, such secondary addresses contained additional information about the borough, municipality or the locality of the companies (e.g. BOULOGNE BILLANCOURT, PARIS; SCHAERBEEK, BRUSSELS; RICHMOND, LONDON) Street addresses can be subject to changes through city council decisions, and postal code conventions can be updated and changed. For instance, after the unification of German Democratic Republic and Federal Republic of Germany, the postal code convention was updated to include 5 digits. Similarly, if a second street address or postal code was listed for the same company in the Bureau Van Dijk database, we retained secondary and tertiary street addresses or postal codes to match company addresses with publication addresses based on this additional information. We used this information while making assignments based on street addresses and postal codes. Changes to the company addresses are very uncommon and address information is consistent over time. Our construction of address information for companies is based on unique BVD IDs in Orbis database. Orbis database introduces changes to BVD IDs (i.e. a company can be identified by multiple BVD IDs) but they do not assign the same BVD ID to multiple companies (i.e. a BVD ID cannot identify more than one company).

Cleaning and standardizing address fields can result in loss of information when city names from the company address database have alternative spellings due to special characters or different spellings in English (e.g. KÖLN, KOLN, KOELN, COLOGNE). For such city names, we added different spelling variations of the names to be able to include them in our sample. Similarly, we screened for further problems like, missing characters in city names after manually screening city fields in our database (e.g. COLOGNE - COLO NE). After looking up exact information in the company address fields, possible problematic assignments were filtered manually. We made the initial assignments based on street addresses of companies if

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di DALAY HAKKI DOGAN
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an exact match was possible based on street address. Then, we used postal codes to assign corporate publications to the specific business unit. If neither of these two fields resulted in a clear assignment to a business unit, we made the assignment based on city information. The region information was generally not informative and we used it only after including all possible variations of city names. If the region information was not informative, we use country information to make the final assignment. Some companies in our ownership database appear only as a single unit corporation. In such cases, we assign publications directly to the single business unit with available information.

For the remaining publications that we could not assign to a business unit based on the available address information for business units, we use the country information to discard matches to non-European business units. At the end of this procedure, if there are remaining publications that have the name of the company appearing in the publication address field, but without a clear assignment to a business unit, we check for the country of the headquarters in the address field and make the assignment to the headquarters.

Based on this procedure we end up with 96997 publications assigned to European business units and 42221 citations made to these publications in patent applications. We find a total of 216,530 patents belonging to European business units, granted by the United States Patents and Trademark Office (USPTO) during the period of 1976-2007. For our analyses, we restrict our attention to groups that have at least 3 publications and 3 patents during the analysis period of 2000-2007. This allows us to use 100418 patents, and 63437 publications belonging to 268 business groups with 2034 business units.

4. Matching Non-Patent Literature Citations to Web of Science Records

We also use the non-patent-literature (NPL) citations listed on the first page of patent applications filed at the USPTO.

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di DALAY HAKKI DOGAN
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In this step, we compile the citations made to corporate publications in all patent applications by any company. Based on the names of authors, name of the scientific journal, title of the publication, and address information of the authors, we use a matching algorithm that generates matches of non-patent literature citations in USPTO applications to the above-described set of corporate publications, even when the citation is listed in a foreign language. Due to the size of the data we are using in this step, we use a fuzzy matching algorithm that generates many false positives, along with proximity scores that demonstrates the maximum and minimum edit distances of the string in the NPL field of the patent documents, to the four fields of information on publications. In our cleaning work, we standardize the non-patent literature citations of patents and the scientific publication addresses, titles, journal information and author names to exclude special characters. We look for exact matches between the four fields of information on publications, and the non-patent literature citation field. Then, we use the proximity scores from the initial match, along with separate string similarity scores between the non-patent literature citations and the four fields mentioned above to discern the correct matches to non-patent literature citations. When in doubt, we rely on the first author in the publication field to confirm the NPL citation made in the patent application to a corporate scientific publication. We make a manual screening of the resulting matches and filter out the mismatches based on frequencies of author names.

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Appendix B. Tables & Figures Pertaining to Data Construction

Table B.1

Source of Problem	**Manifestation of the Problem**	**Our Approach**
Local Language Address Conventions	Company Address in Local Address Conventions (Bayer Strasse; Robert Bosch Strasse, Via Marconi; Avenue Louis Pasteur, Rue du Général Renault)	This problem Is widespread within publication addresses and company addresses. Standardization leads to loss of information. We drop street conventions in company address fields but leave them untouched in publication addresses avoid problems.
Public – Private Collaborations with Similar Names	Bayer Institute in West Virginia United States; Phillips Graduate University in Los Angeles	We manually screen such instances and make assignments based on address information.
Changes to Postal Codes in Countries	D – 1986 to 11986	We use the information available from Orbis database.
English Exonyms for Local Names	Bruxelles, Den Haag, Dunkerque, Firenze, Milano, München, Napoli, Normandy Nürnberg, Roma, Seville, Vienna, etc.	We use alternative spellings, and if possible, longest common strings (MILAN, NORMAND, BRU)
Changes and English Exonyms in Country Names	Belgique, The UK, Italia, Deutschland, Federal Republic of Germany, Democratic Republic of Germany	We include alternative country names as well as abbreviations, FED REP GER, W GER, Wales, Scotland, England, Northern Ireland etc.
Collaborations	Business units can collaborate with other business units of the same group. Single assignments lead to loss of information	We check the instances of company names in limited to limit the loss of information.
Database Restrictions	Special characters that were unrecognized by source database at the time of entry transferred into corrupted characters	We trace the instances of these characters[9] and match after replacing these characters as well.

[9] We use the Stata function “charlist”

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di DALAY HAKKI DOGAN
discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2020
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Database Restrictions	NPL citations, publication titles and source journal name can be written in other languages.	While the NPL-Publication matching takes this into account, we rely on author names in problematic cases, so as to reduce this problem.
Database Restrictions	Strings fields can be cut short before all information fits in	We make manual screenings at the end of string fields to reduce the loss of information.

United States Patent (10) **Patent No.: US 7,058,133 B2**
Menzl (45) **Date of Patent: Jun. 6, 2006**

PROCESS FOR DIGITAL COMMUNICATION AND SYSTEM COMMUNICATING DIGITALLY

Inventor: **Stefan Daniel Menzl**, Jona (CH)

Assignee: **Phonak AG**, Stafa (CH)

Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 631 days.

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(Continued)

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EP	0 341 995	11/1989

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Mosch et al.; A 660-uW 50 Mops 1-V DSP for a Hearing Aid Chip Set; 2000 IEEE; Nov, vol. 36.*

Figure B.1: United States Patent conferred to Phonak AG in Stafa, Switzerland

Manuscript received April 4, 2000; revised June 16, 2000.

P. Mosch and N. Rougnon-Glasson are with Xemics SA, 2000 Neuchâtel, Switzerland (e-mail: philippe.mosch@xemics.com; nicolas.rougnonglasson@xemics.com).

G. van Oerle and S. Menzl are with Phonak AG, 8712 Staefa, Switzerland (e-mail: gerardo@phonak.ch; stefanm@phonak.ch).

K. Van Nieuwenhove and M. Wezelenburg are with Frontier Design, 3001 Leuven, Belgium (e-mail: koen_vannieuwenhove@frontierd.com; mark_wezelenburg@frontierd.com).

Publisher Item Identifier S 0018-9200(00)09420-8.

Figure B.2: Author addresses for Mosch et al., 2000, originating from the same business unit.

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United States Patent (10) **Patent No.: US 7,060,460 B2**
Necina et al. (45) **Date of Patent: Jun. 13, 2006**

METHOD FOR RECONSTITUTING A RECOMBINANT PROTEIN TO ITS BIOLOGICALLY ACTIVE FORM

Inventors: **Roman Necina**, Vienna (AT); **Robert Schlegl**, Vienna (AT); **Alois Jungbauer**, Vienna (AT); **Christine Machold**, Vienna (AT)

Assignee: **Boehringer Ingelheim Austria GmbH**, Vienna (AT)

Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

Appl. No.: **10/261,508**

Filed: **Oct. 2, 2002**

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Lilie, H., et al., "Prolyl isomerases catalyze antibody folding in vitro," *Prot. Sci. 2*:1490-1496, Cambridge University Press (1993).

Figure B.3: NPL citation to Lilie et al., 1993 in USPTO application 7060460 by Boehringer Ingelheim Austria GMBH, a business unit of Boehringer Ingelheim

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di DALAY HAKKI DOGAN
discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2020
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Protein Science (1993), *2*, 1490–1496. Cambridge University Press. Printed in the USA.
Copyright © 1993 The Protein Society

Prolyl isomerases catalyze antibody folding in vitro

HAUKE LILIE,[1] KURT LANG,[2] RAINER RUDOLPH,[2] AND JOHANNES BUCHNER[1]
[1] Institut für Biophysik und Physikalische Biochemie, Universität Regensburg, 93040 Regensburg, Germany
[2] Biochemical Research Center, Boehringer Mannheim GmbH, Nonnenwald 2, 82377 Penzberg, Germany

(RECEIVED April 9, 1993; REVISED MANUSCRIPT RECEIVED June 1, 1993)

Figure B.4: Author address information for Lilie et al. 1993, 2000, originating from a different business unit of the same corporate group.

United States Patent (10) **Patent No.: US 6,528,501 B1**
Leysen et al. (45) **Date of Patent: Mar. 4, 2003**

22S-HYDROXYCHOLESTA-8, 14-DIENE DERIVATIVES WITH MEIOSIS REGULATING ACTIVITY

Inventors: **Dirk D. Leysen**, Lommel (BE); **Jaap J. van der Louw**, En Oss (NL); **Robert Gerard Jules Marie Hanssen**, Heesch (NL); **A. Anja Wiersma**, He Elst (NL)

Assignee: **Akzo Nobel N.V.**, Arnhem (NL)

Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

Appl. No.: **09/857,731**

PCT Filed: **Jun. 10, 1999**

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Byskov. A. G. et al.: "Chemical Structure of Sterols That Activate Oocyte Meiosis", Nature, vol. 374, No. 6522, Apr. 6, 1995, pp. 559–562.

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C. Grondahl et al.: "Meiosis Activating Sterol Promotes Resumption of Meiosis in Mouse Oocytes Cultured In Vitro in Contrast to Related Oxysterols", p. 417, col. 1. Chemical Abstracts, vol. 129, No. 4, Jul. 27, 1998, abstract No. 39307.

C. Grondahl et al.: Biological Reproduction, vol. 58, No. 5, 1998, pp. 1297–1302.

R. J. Chorvat et al.: "22–Hydroxycholesterol Derivatives as

Figure B.5: USPTO Patent 6528501 citing Grondahl et al., 1998 in its NPL citations.

BIOLOGY OF REPRODUCTION **58,** 1297–1302 (1998)

Meiosis-Activating Sterol Promotes Resumption of Meiosis in Mouse Oocytes Cultured In Vitro in Contrast to Related Oxysterols

Christian Grøndahl,[1,2] Jan L. Ottesen,[2] Monika Lessl,[3] Peter Faarup,[2] Anthony Murray,[2] Frederik C. Grønvald,[2] Christa Hegele-Hartung,[3] and Ian Ahnfelt-Rønne[2]

Health Care Discovery,[2] Novo Nordisk A/S, Copenhagen, Denmark
Research Laboratories,[3] Schering AG, Berlin, Germany

Figure B.6: Grondahl et al. 1998 is a publication by a team of scientists from Schering AG and Novo Nordisk A/S.

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United States Patent
Platzek et al.

(10) **Patent No.: US 6,908,989 B2**
(45) **Date of Patent: *Jun. 21, 2005**

PROCESS FOR THE PRODUCTION OF PERBENZYLATED 1-O-GLYCOSIDES

Inventors: **Johannes Platzek**, Berlin (DE); **Ulrich Niedballa**, Berlin (DE); **Klaus-Dieter Graske**, Berlin (DE)

Assignee: **Schering AG**, Berlin (DE)

Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 232 days.

This patent is subject to a terminal disclaimer.

Appl. No.: **10/174,508**

Sugawara et al., "Synthesis of ω–(methoxycarbonyl)alkyl and 9–(methoxycarbonyl)–3,6–dioxanonyl glycopyranosides for the preparation of carbohydrate–protein conjugates," Carbohydrate Research, Elsevier Scientific Publishing Company, Bd. 230, Nr. 1, 1992 Seiten 117–150.

Schmidt et al., "1–O–Alkylation of D–Glucopyranose," Journal of Carbohydrate Chemistry, Bd. 3, Nr. 1, 1984, Seiten 67–84.

O. Lockhoff, "An Access to Glycoconjugate Libraries through Multicomponent Reactions," Angewandte Chemie International Edition, Bd. 37, Nr 24, 1998, Seiten 3436–3439.

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Primary Examiner—Elli Peselev
(74) *Attorney, Agent, or Firm*—Millen White Zelano & Branigan P.C.

Figure B.7: NPL citation to Lockhoff, 1998 in a USPTO application by Schering AG from 2002 (business unit of Bayer AG as of 2006).

An Access to Glycoconjugate Libraries through Multicomponent Reactions

Oswald Lockhoff*

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Figure B.8: Author address for Lockhoff, 1998 indicates Bayer AG Central Research unit as the origin.

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Chapter 2

How mixed ownership affects decision making in turbulent times: Evidence from the digital revolution in telecommunications*

David Wehrheim† Hakki Dogan Dalay‡ Andrea Fosfuri§ Christian Helmers¶

ABSTRACT

This study examines how the ownership structure of corporations shapes their responses to technological change. We predict that mixed ownership, a situation in which, following privatization, the shares of a company are partly privately held and partly held by the government, is associated with lower responsiveness to technological change. We theorize that the top management of corporations with mixed ownership is exposed to conflicting views regarding how companies should address the challenges posed by technological changes, thereby making them more likely to maintain the status quo. In addition, we argue that mixed ownership is particularly problematic when firms attempt to integrate extramural technology to manage technological transformation. Our data on European telecommunications operators that had to adapt to the advent of Internet-based communication services support our predictions.

KEYWORDS: digitization, innovation, mixed ownership, ownership structure, privatization, telecommunications industry

JEL Classification: G32, G38, L33, L96, O31, O33

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1. Introduction

The privatization wave, which started under U.K. Prime Minister Thatcher and. U.S. President Reagan in the 1980s and spread across the globe during the 1990s, produced what is arguably the greatest transfer of ownership in the history of corporations. Governments worldwide have sold, or are selling, large shares of corporate ownership to the private sector. Global privatization transactions were estimated at almost one trillion dollars during the period between 2013 and 2016 (Privatization Barometer, 2016). While a vast literature has examined the impact of privatization on the economic and financial performance of divested firms (for reviews, see Megginson and Netter, 2001; Estrin et al., 2009), we have limited understanding of the governance conflicts that can arise when governments retain residual ownership after privatization and of the resulting implications for strategic decision making (Hoskisson et al., 2002; Koenig et al., 2013).

In this paper, we bridge this gap by integrating two streams of literature: the literature on corporate governance and that on organizational adaptation to discontinuous technological change. Corporate governance research usually relies on the assumption that ownership consists of a homogeneous constituency. However, as documented by Hoskisson et al. (2002) in the context of innovation strategies, different owners often have their own distinct and potentially conflicting preferences regarding strategic options. As such, the government, for instance, might pursue social and political objectives (Fogel et al., 2008) that are not necessarily in line with the profit or value maximization objectives of private owners (Boubakri et al., 2013). These different preferences over strategic options are likely to affect the effectiveness of top management's strategic decision making, thereby leading to suboptimal strategic choices (Boubakri et al., 2005).

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We examine how different constituencies of owners and their potentially conflicting preferences impact a firm's ability to respond to changes in the external environment by examining the specific case of discontinuous technological change. Discontinuous technological change is an appropriate setting to study this research question because it requires strategic renewal outside the frame of the current strategy (Huff et al., 1992) and, in most cases, an entirely new set of capabilities (Tushman and Anderson, 1986). Formulating such a strategy is easier and quicker when ownership is concentrated among a homogeneous constituency, which has been theorized in the family business literature as an important determinant of variations in incumbents' responses to discontinuous innovation (Koenig et al., 2013). Instead, when both the government and private investors are residual owners (which we refer to as 'mixed ownership'), the former can resist strategic choices that do not align with its social and political goals. As we argue, this resistance increases the complexity of the decision-making process regarding the strategy required to move forward and consequently affects when and how established players respond to discontinuous technological change. More specifically, we hypothesize that, in these situations, the top management team is more inclined to maintain extant business models and delay adaptation. We therefore predict a negative association between mixed ownership and a firm's response to discontinuous technological change. To provide additional evidence for the mechanism at play, we distinguish new technologies that result from internal development from those acquired externally. Many of these externally acquired technologies are the outcomes of corporate acquisitions, an important lever in the pursuit of adaptation following a technological discontinuity (Rothaermel, 2001; Puranam et al., 2006). Since the prior literature has emphasized that these decisions are specifically prone to greater shareholder conflicts (Shleifer and Vishny, 1997; Bae et al., 2002), we expect them to be particularly penalized by mixed ownership.

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We test these predictions in the context of the European telecommunications industry during the period of 2000-2013. In the late 1980s, most European telecommunications markets had one fixed-line operator that owned a network originally built with public money. At the time, European governments initiated a privatization process, which in many cases entailed partial stock flotations undertaken in several waves. Despite ongoing privatization, most markets were still insulated from competition and were growing at double-digit rates. However, since the early 2000s, the industry has undergone dramatic technological change due to the advent of digitization (Greenstein et al., 2013; Bughin and Van Zeebroeck, 2017). Telecommunications operators' revenues from their traditional core services, voice telephony and text messages, rapidly began to dwindle; these standard business models gave way to alternative, Internet-based services that were able to largely circumvent operators. The combination of a faltering traditional business model, a universally shifting paradigm toward digital content, and the need to regain weight in an environment dominated by new players in the industry has caused telecommunications operators to enter the playing field so far occupied by technology companies, such as Apple, Microsoft, Google, Facebook, etc.

The large impact of this transformation on telecommunications operators is well illustrated by the example of the Spanish Telefonica Group. In an attempt to regain ground, Telefonica underwent profound restructuring involving the creation of a new business unit: Telefonica Digital. The new business unit of Telefonica focused on steering Telefonica's global business toward the creation and marketing of digital services, including Internet services, cloud computing, videos, e-financial services, and mobile advertising. Similar efforts to restructure fundamentally the business model of telecommunications operators were documented by Van Kranenburg and Hagedoorn (2008) in their case study of three other European companies: KPN, Deutsche Telekom and British Telecom.

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Another advantage of focusing on the European telecommunications industry is that decisions about initial privatizations and most stock flotations occurred before the digitization disruption occurred and were related to fiscal pressures in preparation for European market integration. This timing substantially reduced concerns about the potential endogeneity of privatization with regard to this specific decision about technology. We recognize, however, the possibility that governments, in more recent years, could have decided to retain ownership based on operators' performance in the digital space and its determining factors. We account for this issue in the empirical analysis.

Finally, from an empirical standpoint, the telecommunications industry offers a unique opportunity to identify the impact of the digital transformation using a clear definition of digital technologies based on patent classes. Moreover, patenting is an important mechanism for telecommunications operators to protect their intellectual property in digital areas. Returning to the example of Telefonica, as part of the restructuring, the company created an internal 'R&D Patent Office' to ensure that the group created a patent portfolio in an environment in which patents are seen as an integral part of the new business model. Data from Fink et al. (2016), which cover 13 OECD economies, in fact show that the surge in patenting propensities in information and communication technologies during the 2000s was partly due to an extremely fast growth in filings on digital communication technologies; filings increased in absolute terms by almost 15% per year between 1995 and 2008, outstripping by far the R&D growth rate in the sector. This fact underscores the importance of patents for telecommunications operators in digital technologies and implies that patents are likely to capture well any innovative activities of operators in this space.

Our findings indicate that operators with mixed ownership respond substantially less aggressively to the digital challenge. More precisely, telecommunications operators with mixed

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ownership invest approximately 70% less in the development of digital capabilities compared to firms that are either fully private or in which the government owns a majority of shares. Further, when we distinguish new technologies that result from internal development from those acquired externally, our results reveal that, while mixed ownership hinders both means of technology adoption, it is particularly detrimental to the acquisition of extramural technologies. This finding is consistent with the underlying mechanism that we propose. Finally, we show that the stock market awards higher valuations of firms with patents in the digital space, suggesting that the sluggish response to technological change associated with mixed ownership harms investors and companies.

Our paper contributes to the literature in several ways. First, we add to corporate governance research by examining the consequences of potential conflicts among different key owners of a firm. Our results suggest that the presence of different constituencies in a firm's ownership creates inefficiencies in strategic decision making because strategy formulation becomes more complex, more challenging and certainly more political. While this finding confirms the findings of Hoskisson et al. (2002) and the propositions set forth by Koenig et al. (2013), a unique feature of our setting is that ownership is determined exogenously as an outcome of long-term privatization processes. Second, we contribute to the innovation literature by offering a novel explanation for the heterogeneity in incumbents' responses to discontinuous technological change (Tripsas, 2009; Henderson, 1993; Christensen, 1997; Kammerlander and Ganter, 2015; Kaplan, 2008). To the best of our knowledge, the role of mixed ownership has been only theoretically explored in the family business context (Koenig et al., 2013) despite its importance in many firms, industries and countries. Finally, we contribute to the privatization research by identifying a novel mechanism through which ownership structure might affect performance. While there is considerable evidence supporting the view that state-owned

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companies are less efficient than private companies, recent research has suggested that government ownership might in fact help when it can affect regulatory policies and control of scarce resources (Zhou et al., 2017). Our findings, in contrast, indicate that, in the presence of discontinuous technological change, the combination of private and government ownership has negative effects on companies.

1. Theoretical framework

The separation between ownership and control is a cornerstone of modern firms. In well-functioning capital markets, investors diversify their wealth by supplying capital to public companies, without spending resources to monitor them. However, the separation between ownership and control does not always work perfectly. La Porta et al. (1999, 2002) showed that large shareholders often participate in the management of public companies, taking advantage of their controlling positions to influence business decisions in ways that benefit them and harm other shareholders. In the context of family firms, in which the large shareholder in the position of 'expropriation' is an individual or a family, Villalonga and Amit (2006) showed that, when the CEO is not the founder but a descendant, the conflict between shareholders is costlier and overshadows the classic owner-manager conflict, a la Jensen and Meckling (1976). These findings have led to the development of a new perspective on corporate governance, which focuses on the conflicts between different sets of principals in the firm.

In this paper, we are interested in the agency issues that arise when both the government and private investors are residual claimants in the corporate structure. In particular, we restrict our attention to 'mixed-owned' firms, which we refer to as organizations in which the government does not have full control but nevertheless exerts influence (see Eckel and Vining, 1985). In

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2012, these minority-owned state entities accounted for more than 90% of state-invested listed entities in OECD member countries (OECD, 2014). This form of ownership is typically the direct consequence of privatization processes in industries formerly characterized by the presence of state monopolies. From a corporate governance perspective, privatization is an interesting context in which to study the implications of changes in the ownership structure (and related problems) because ownership transfers from the state to the private sector create new agency relationships, and these new owners should be concerned about managerial perquisite consumption and problems related to entrenchment (Dharwadkar et al., 2000).

Research on private versus public ownership, in contrast, has predominantly focused on the implications for economic performance (for reviews, see Megginson and Netter, 2001; Estrin et al., 2009). For instance, Estrin and Perotin (1991) argued that state ownership renders corporations inefficient because it often substitutes profit maximization with political objectives. Shleifer and Vishny (1993) pointed out that government interventions in corporate decisions often result in bribes. Empirical evidence seems to support this notion. For instance, Boardman and Vining (1989), La Porta et al. (2002) and Sapienza (2004) found that government ownership harms firm value, suggesting that governments have more room to distort business decisions in firms in which they own a larger proportion of shares. However, recent research has challenged these findings by showing how various forms of state ownership foster firms' performance (Inoue et al., 2013; Musacchio et al., 2015). In this vein, Zhou et al. (2017) found that state ownership might be helpful in countries and industries in which control over regulatory policies and scarce resources is critical.

The mixed findings of previous studies have emphasized the need to recognize potential conflicts among state and private investors, rather than considering the ownership-performance relationship to be a black box. From the perspective of research on privatization, we therefore

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believe that this focus could provide us with a finer-grained picture of why some privatization efforts succeed while others fail. Below, we focus on the implications of such conflicts for a key strategic decision: the response to discontinuous technological change. Discontinuous technologies deviate from previous trajectories by shifting the technological limits upward (Henderson and Clark, 1990) and provide sharp price-performance improvements over the existing technology (Tushman and Anderson, 1986). Such innovations typically possess radically new features, involve fundamentally new processes, require new competences, and/or are based on new business models. In the Tushman-Anderson framework, they are classified as competence-destroying innovations because they require ‘new skills, abilities, and knowledge in both development and production of the product’ (p. 442). Incumbent firms have difficulties coping with technological discontinuities and often ultimately lose their technological leadership (Christensen, 1997; Greenstein et al., 2013; Bughin and Van Zeebroeck, 2017).[1]

Responses to such technological shocks require both the formulation of a transformational strategy and coordination across different organizational layers, which depend on choices and decisions by the board of directors (Baysinger et al., 1991). Considering the role of the ownership structure in the composition and decision making of boards of directors (Li, 1994), the ownership structure of the corporation is likely to play a crucial role in the response to discontinuous technological change. Indeed, given the disruptive nature of technological change, the appropriate response can often require decisions and actions that completely transform a corporation and its business model (Markides, 1997).[2] Formulating such a transformational strategy is easier and quicker when ownership consists of a homogeneous constituency. Instead, when faced with conflicting preferences over the strategy required to move forward, a firm’s top management might postpone decisions that entail organizational change and continue to rely on existing routines and competences (Hoskisson et al., 2002).

Tesi di dottorato "Essays on Corporate Science and Technological Change"
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While government and private owners might recognize the need to adjust to discontinuous technological change to ensure the survival of the corporation, their preferences regarding how a company should change might differ, thereby creating hurdles for strategic decision making. For instance, private owners might prefer to seek collaboration with a foreign firm through the injection of capital and the sourcing of extramural technology. This solution might imply rapid divestment from the traditional lines of business with significant employee layoffs. Instead, the government might prefer to boost internal investment in basic research to manage technological change and transform the company into a national champion. This solution might be achieved by channeling public money into the venture and by preserving current investments and jobs. More generally, while private owners and the state might agree about the need to react to discontinuous technical change, they are likely to have different views about how to react. Indeed, the government might be less concerned about profit maximization and instead focus on issues concerning welfare, national security and national pride (Mazzolini, 1981; Boardman et al., 1986).

A company's top management will find it easier to coordinate a response to discontinuous technological changes when the entire firm is owned privately or when the firm is controlled by the state. However, in a mixed ownership condition, in which the state can influence decisions, albeit not unilaterally control them, top management faces the challenge of attempting to find policies in the 'possibility set' of owners with diverse and sometimes conflicting views about how to adapt to technological change. Such divergence in preferences is likely to be reflected in corporate restructuring decisions. In their extensive survey of the research on transition economies, Djankov and Murrell (2002) found that privatization to outsiders is associated with more frequent restructuring processes than privatization to insiders. When multiple owners, such as investment funds, foreign investors and other outsiders are

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present, restructuring occurs ten times more often in former state-owned monopolies than when ownership is dispersed. Most important for the purposes of our study, privatized firms with mixed ownership seem to be subject to restructuring decisions more frequently.

Our logic is akin to that underlying the growing literature on hybrid organizations. This literature has advanced the notion that, when organizations have multiple goals (for instance, profit maximization and sociopolitical goals or profitability and sustainability), they are more likely to suffer from mission drift, organizational paralysis, strategic inconsistency and slower decision making (Battilana and Dorado, 2010; Fosfuri et al., 2016). As Lazzarini and Musacchio (2018) argued, the existence of state owners exacerbates conflicts because the government creates discretionary pressures on a corporation to pursue a political and social agenda, rather than the corporation voluntarily pursuing its own goals. Thus, because the top management of firms with mixed ownership must respond to different principals (Eckel and Vining, 1985), it is exposed to 'organizational cognitive dissonance' (Boardman and Vining, 1989), which keeps them from focusing adequately on exogenous technological challenges.[3]

While the discussion above does not provide a clear prediction of whether firms with private ownership respond to technological changes more or less aggressively than state-owned firms, it nonetheless suggests that corporations that are 'stuck in the middle' generate slower and less radical responses than firms with either private or state ownership. Therefore, we posit the following.

> ***Hypothesis 1****: Firms with mixed ownership display a weaker response to discontinuous technological changes than firms that are either fully private or in which the government owns a majority share.*

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So far, we have explored how mixed ownership affects the intensity of a firm's response to discontinuous technological change. Below, we focus on the mode of adjustment and investigate the channels through which firms respond to discontinuous technological change.

Companies might develop new technological knowledge internally, or they might resort to external sources (Cassiman and Veugelers, 2006). In recent decades, the development of technology markets (Arora et al., 2001) and increasing use of corporate acquisitions to source externally developed technology (Sears and Hoetker, 2013) have offered new channels to incumbent firms to manage rapid and discontinuous technological change (Rothaermel, 2001; Puranam et al., 2006).

However, acquiring externally developed technology through corporate acquisitions is a major strategic decision (Hitt et al., 2001) subject to additional challenges. For instance, individuals have an attitude bias toward knowledge acquired from outside of the organization (see, e.g., Katz and Allen, 1982; Antons and Piller, 2015). Scholars from different research fields have acknowledged the tensions between acquiring and integrating external knowledge and have emphasized the crucial role played by absorptive capacity (Cohen and Levinthal, 1989; Zahra and George, 2002; Puranam and Srikanth, 2007). While the internal development of new technological competencies to respond to discontinuous technological change requires the formulation of a complex, challenging and transformative strategy, these difficulties are magnified when these competences are sourced through corporate acquisitions (Shleifer and Vishny, 1997; Bae et al., 2002). It is thus crucial to have a cohesive board that makes bold decisions. Greve and Zhang (2017) showed that mixed ownership is a debilitating factor in mergers and acquisitions because of both its external influence (through ownership) and its internal influence (through shared decision making). According to this, state ownership renders a firm less likely to engage in mergers and acquisitions, while the presence of external owners

Tesi di dottorato "Essays on Corporate Science and Technological Change"
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makes it more likely to engage in mergers and acquisitions. Indeed, their findings indicated that investors view mergers and acquisitions by firms with mixed ownership skeptically. Chen and Young (2010) showed that conflicts of preferences between the government and private investors are particularly acute in mergers and acquisitions because the former can be guided by political motives that might lead to deals that destroy shareholder value. This outcome, in turn, could cause firms with mixed ownership to engage in fewer mergers and acquisitions.

We submit here that the top management of firms with mixed ownership will find it even more difficult to implement technology sourcing strategies to adjust to discontinuous technological change because these strategies combine the challenges of both major strategic change and corporate acquisition. Thus, while we expect that mixed ownership negatively affects both internal knowledge development and external knowledge acquisition, the latter mode of response will be subject to greater internal conflicts and will more likely be slower. Hence, we expect the following.

> ***Hypothesis 2****: In response to discontinuous technological change, firms with mixed ownership resort relatively less often to externally developed technology than firms that either that are fully private or in which the government owns a majority share.*

3. The telecommunications industry

3.1. Digitization as a radical technological discontinuity

Our setting is the radical technological change in the telecommunications industry caused by the advent of digital technologies and Internet-based communication services. Specifically, we refer to digitization in the telecommunications industry as the diffusion and commercialization of Transmission Control Protocol/Internet Protocol (TCP/IP)-based services and applications. The change occurred as telecommunications networks transitioned from so-called second

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generation (2G) to third generation (3G) networks capable of supporting a wide range of packet-based (always-on) data services, including audio, video and multimedia messaging. This digitization has triggered the entry of new competitors with different sets of resources and capabilities and the technological convergence of the previously distinct industries of telecommunications, information, media, entertainment and consumer electronics (see, e.g., Peppard and Rylander, 2006; Tilson and Lyytinen, 2006; Funk, 2009).

As an illustration, we consider communication systems based on Voice over Internet Protocol (VoIP) technology.[4] VoIP is a methodology and group of technologies for the delivery of voice communications and multimedia sessions over IP networks. It enables an Internet-based method for making phone calls or sending content to end consumers at almost zero cost since it bypasses telecommunications incumbents' billing systems for voice and text messaging and, consequently, their main source of revenue. Highly innovative companies, such as Skype, Microsoft, Google, Facebook, WhatsApp or Jajah, suddenly became direct competitors with telecommunications operators by offering (mobile) VoIP as part of their broader Internet-based business. As described by Benner (2010), Vonage introduced digital VoIP in March 2002, followed by Skype offering free Internet VoIP telephony in August 2003.

The importance of digital technologies and their potentially dramatic impact on the business of incumbents have not gone unnoticed by industry experts and observers.[5] Echoing industry reports (e.g., ETNO, 2016), falling revenues and average revenues per user, profit warnings and persistently high levels of debt despite growing usage are only some of the metrics that illustrate how telecommunications operators are struggling with new competitors, products and business models. Thus, digitization created an urgent challenge for the management of incumbent firms in this industry to find new business models and sources of income to secure competitiveness

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in the digital world. Therefore, we believe that this context provides a natural setting to examine the factors that shape firms' responses to technological discontinuity.

3.2. Privatization processes of European incumbent operators

Our aim in this section is to describe the origins of (and reasons for) the heterogeneity in mixed ownership that we observe in our data. During the 1980s, European telecommunication services were usually provided by state-owned monopolies regulated as utility providers. The main exception was the UK, where in July 1982, the Secretary of State at the Department of Industry pronounced the intention to sell shares in British Telecommunications (BT). The motives for privatization were not so much fiscal pressure but rather political and economic party ideology and the desire to follow the example of the United States (Thatcher, 1999). The company's transfer into the private sector started in November 1984 and, after subsequent flotations, was completed in July 1993.[6]

Elsewhere in Europe, the liberalization of telecommunications markets began only in the 1990s. The main trigger of change was a July 1993 EU Council of Ministers resolution that required member states with the largest networks to open their markets to full competition in voice telephony from 1 January 1998, although a number of them chose to introduce full competition before this date (Schmidt, 1998).

While the European Commission stopped short of actively promoting privatization, the liberalization of markets had an important effect on incumbents' ownership structures (Monsen, 2004). First, most governments realized that the ability to raise new capital without being constrained by government borrowing restrictions would be useful for securing funding to invest in the modernization of telecommunications infrastructure. Second, in light of the opening of telecommunications markets in 1998 and with the aim of encouraging companies to

Tesi di dottorato "Essays on Corporate Science and Technological Change"
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operate efficiently (Newberry, 2001), governments embarked on either partial or full privatization (Eliassen and From, 2017). In addition, the Maastricht Treaty's fiscal criteria to qualify for joining the European Monetary Union placed substantial pressure on most governments' finances. It is therefore unsurprising that the peak of privatization in Europe occurred during the same period. In Spain, for example, revenues from the last public offerings in October 1995 and February 1997 amounted to 4,886 million EUR (Bel and Trillas, 2005).

By 1998, BT in the UK and Telefonica of Spain had been wholly privatized, while Deutsche Telekom, KPN of the Netherlands, Tele Danmark and Telecom Italia, for example, had been partially privatized, and planned sales of shares were well advanced for Telenor of Norway and Telia of Sweden. The sale of the first tranche of shares in Deutsche Telekom, in 1996, was the largest single privatization issue in the European Union to date. This demonstrates that changes in ownership and market liberalization did not follow the same chronological order across countries. Some countries, such as the UK, privatized at an early stage, long before experiencing a fully liberalized market, while some privatized more as a result of market liberalization (e.g., Germany). Furthermore, others liberalized their telecommunications markets at early stages but privatized at later stages (e.g., Sweden). Second, it is important to note that some governments divested slowly and partially (e.g., the Netherlands), while others made a rapid and full transfer of ownership and control (e.g., Denmark).

Overall, the privatization process in Europe has left the industry with very heterogeneous players in terms of their ownership structures. This degree of heterogeneity is reflected in our sample of European telecommunications operators for the period between 2000 and 2013. One-third of our observations are characterized by mixed ownership; the average share of state ownership is around 20%. We also observe that the bulk of variation is across firms rather than within firms over time: the average within-firm standard deviation of government ownership

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discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2020
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levels is 0.05, while the standard deviation across firms has an average value of 0.24. This implies that for European telecommunications operators, the bulk of privatization decisions were made before the beginning of our sample period. This is useful, as it reduces concerns about endogenous responses in ownership structure to digitization, which was in full swing in the telecommunications industry during our sample period.

1. Data and methods

To understand how telecommunications operators responded to digitization in the presence of mixed ownership, we study European-based network operators in the years from 2000, the first year from which we have information about the group structures and subsidiaries, as provided in Bureau Van Dijk's (BVD) Amadeus database, to 2013, the last year from which we can realistically construct measures based on patent application data. The operators are drawn from Business Monitor International's telecommunications reports, which cover general and operator-specific market data, operator profiles, company histories, financial information, and telecommunications network and service information. Apart from providing detailed data on the telecommunications industry, these reports also allowed us to identify the complex ownership structures of European operators. We identified a total of 24 telecommunications operators of interest to our study (see Table I). We limited the sample to these 24 operators instead of considering the entire telecommunications industry for several reasons. First, these companies are the ultimate owners and residual claimants of much of the pan-European telecommunications industry. In fact, these firms represent approximately 70% of the capital expenditure in fixed networks and 83% of employment in the EU's 28 telecommunications markets (ETNO, 2016). Second, these firms are also appropriate for examining our research question because all of them are owners of the telecommunications infrastructure, which

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requires extremely high sunk costs that render exit almost impossible (i.e., compared to mobile virtual network operators).

[INSERT TABLE I ABOUT HERE]

Patent data are used to construct indicators of operators' technological activities. There are numerous advantages of using patent measures (Pavitt, 1985; Griliches, 1990; Hall et al., 2005): patent documents contain detailed information about the content and ownership of patented technology; they cover a broad range of technologies; patent data are 'objective' in the sense that they have been processed and validated by patent examiners; and patent data are publicly available. Like any indicator, however, patents are also subject to a number of well-known drawbacks: not all technological activities are patented; patent propensities vary across firms and industries; and patented technological activities differ in their technical and economic value. As we focus on a single industry and on a rather homogeneous set of companies, some of the aforementioned limitations are less of a concern.[7] We construct patent-based variables from patent applications, instead of patent grants. The use of patent applications tends to result in a more complete picture, especially in the case of novel technologies. Moreover, patent-granting decisions by the European Patent Office (EPO), our source of patent data that we retrieved from the EPO Worldwide Patent Statistical Database (edition April 2017), require 5–6 years on average, making patent grants a poor (incomplete) indicator of firms' more recent technological activities.

We first matched patents to all of the companies that were part of any of the business groups in our sample and then consolidated patent filings; i.e., all patents of the parent company and its consolidated (majority-owned) subsidiaries were included. To construct business groups, we used lists of subsidiaries included in corporate annual reports, information from BVD's

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Amadeus database and M&A data from SDC Platinum and Zephyr.[8] The consolidation was conducted on an annual basis (2000–2013) to account for changes in the group structure of operators over time. The use of consolidated patent data allowed us to construct a complete picture of the technological activities of firms since a significant proportion of patents are not filed under the parent firm name, and patent filing strategies might differ across companies. To match firms to patents, we standardized assignee and company names and relied on exact string matching.[9] After manual checks and corrections, we matched 74,216 patent applications to 227 disambiguated assignees.

Dependent variables

Technology adoption. We captured technology adoption through the development of firm capabilities in the digital space, which, following the extant literature, we measured via patent applications stocks [e.g., as in Henderson and Cockburn (1994) or Arora et al. (2014, 2017)]. We used information on patent technology classes [i.e., International Patent Classification System (IPC) four-digit classes] to identify Internet-related telecommunications technologies (IRTs), our proxy for digital technologies, and we separate them from the remaining information and communication technologies (ICTs), which we refer to as non-IRT.[10] To classify patents, we extended the classification proposed by Palmberg and Martikainen (2006), which identified all technology classes that belong to the ICT industry. After consulting with industry experts from Telefonica, Telecom Italia and the Fraunhofer Institute, we defined IRT as technologies that display TCP/IP compatibility and packet-switching compatibility. Among IRT, we included also patent classes associated with new-generation smart phone technologies. All other ICT patent classes were included in the non-IRT category. The precise mapping between patent classes and our two categories of IRT and non-IRT is reported in Table II. In robustness checks, we employed the share of IRT applications within the total stock of the

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firms' ICT applications and introduced citation-adjusted measures for the dependent variable to control for heterogeneity across firms in the scientific value (quality) of their portfolios. We discuss the details below.

[INSERT TABLE II ABOUT HERE]

Mode of adoption. To capture heterogeneity in firms' modes of adoption, we distinguished between patents originally filed by the operator (internally developed patents) and those acquired through the acquisition of another entity. Thus, our main measures were the stocks of IRT patent filings for each of the two modes of adoption. As alternative measures, we also used the share of the stock of IRT patent applications obtained via an acquisition over the total stock of IRT patent applications and a dummy variable with the value of one for every year when a firm undertook an acquisition (Capron et al., 1998; Arora et al., 2014).

Independent variable

For each operator and year, we collected information on both direct and indirect government ownership, i.e., whether the government directly owns firms or instead uses indirect channels of ownership or 'pyramids'. For instance, it is common for governments to hold ownership stakes in certain firms that, in turn, have stakes in other firms and so forth. Whenever available, we attempted to reveal these pyramids and identify state-related owners, including the federal government, state-level governments, sovereign wealth funds, development banks, and other state-related investment vehicles, such as pension and insurance funds. Our main data sources were the shareholder lists available in annual reports. We then created a dummy variable with the value of one when a state-related entity holds a relevant equity stake (i.e., more than 1%) but less than the amount necessary to grant clear control rights (i.e., 50%) and zero otherwise. As explained before, the rationale for this cutoff is that we expect ownership conflicts to be

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particularly present in situations in which the government loses majority control to the private sector but can still exert some influence over firm decision making.[11] However, for robustness purposes and more precision, we also used levels of state ownership and their squared terms, represented by the percentages held of firms' shares.

Control variables

To control for other sources of heterogeneity across firms and years in the response to the digital transformation, we included firm size to account for possible economies of scale (measured as the logarithm of sales), firm age to capture possible life-cycle effects (measured as the logarithm of the difference in years between t and the incorporation year), a firm's R&D stock to reflect the overall investment in knowledge production, and a firm's scientific publication stock to proxy for scientific capability and absorptive capacity (Arora and Gambardella, 1994). Since knowledge becomes obsolete due to the ongoing technological development and actions undertaken by competing firms, those stock variables are calculated using a perpetual inventory method with an annual 15% depreciation rate (δ) following the method described in Hall et al. (2005).[12]

Financial information is extracted from annual reports and BVD's Osiris database, while data on scientific publications come from Thomson Reuters Web of Science. The base model also accounts for differences in business strategy across operators; we include the logarithmic transformation of the total number of fixed-line, broadband, and mobile telecommunications subscribers (collected from annual reports). Finally, all regressions control for year fixed effects and the pre-sample means of the dependent variables, as proposed by Blundell et al. (1999). The ordinary fixed effect estimator is consistent only if the independent variables are strongly exogenous with respect to the error term. Theoretically, such strong exogeneity can be further

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relaxed (to sequential exogeneity or predetermined regressors) if a first-difference estimator is used, together with lagged regressors as instruments. In our case, limited within-firm variation for the regressors prevents instrumentation by lagged variables. Blundell et al. (1999) therefore proposed the pre-sample mean of the dependent variable to proxy for unobserved heterogeneity and showed consistency under an increasing time length of the pre-sample, although the regressors are only weakly exogenous. We follow this procedure (also adopted by, e.g., Galasso and Simcoe, 2011; Aghion et al., 2013; Blanco and Wehrheim, 2017) and use the information on patent applications filed between 1978 (the foundation of the EPO) and 1999 to construct the corresponding pre-sample averages.

Estimation approach

The distribution of the dependent variable(s), a nonnegative integer variable, is distinctly non-normal, approximating a Poisson distribution. Because the assumptions of homoskedastic, normally distributed errors are violated with count variables as the dependent variables of the regression, linear regression is not the most appropriate approach for a count dependent variable. Since a pure Poisson model has the restrictive assumption of the mean equal to the variance, but the data feature overdispersion, i.e., the mean is not equal to the variance, we employ negative binomial specifications (Cameron and Trivedi, 1990). We also include models in which the dependent variable is the share of the stock of IRT patent applications over the total stock of ICT patent applications or the share of the stock of IRT patent applications acquired over the total stock of IRT patent applications, which are ratios that range between zero and one. To avoid the problem of imposing arbitrary limits on the range of variations in our independent variables, we follow the ‘fractional logit’ solution proposed by Papke and Wooldridge (2008).[13]

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Small sample size

To test our theory, we needed a setting in which the ownership structure was reasonably exogenous, in which firms faced an exogenous strategic challenge and in which we were able to capture the extent to which firms respond to this challenge. Obviously, the trade-off was that this choice led to a small sample size. There were two main issues. The first concern was whether our sample size was too small to obtain statistically significant effects. However, even with 24 firms, we identified significant impacts. There were several reasons for this outcome. First, our sample of telecommunications operators was homogeneous in terms of size, region and product mix so that time dummies absorbed most market-wide shocks. Second, these firms are large, so idiosyncratic shocks tended to average out. Third, we invested considerable time in confirming the accuracy of our measures, which therefore had little measurement error. Fourth, we observed these firms over a 13-year period, which provides 303 observations for our empirical analysis. Finally, we had variation in the treatment even within firms: 30% of the firms in our sample were in a different category at the end of the period than they were at the beginning of the period.

The second concern was the type of statistical inference appropriate, given the sample size. Although the use of multiple observations per firm reduces the sample size needed to detect an effect, it comes with the disadvantage that errors might be correlated over time within the panel dimension (i.e., the firm). Because Angrist and Pischke (2009) were skeptical about the reliability of clustered errors when the number of clusters is less than 42, we proceeded as follows: throughout the paper, we show standard errors robust to heteroskedasticity which, in our models, is equivalent to clustering at the firm-year level; in the Appendix, Table A.I, we confirm that our main inferences still hold when we estimate firm-clustered Huber-White and

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wild bootstrap standard errors (for details on the wild bootstrap estimate, see Cameron et al., 2008).

5. Results

Descriptive statistics are presented in Table III. Our sample comprises 303 firm-year observations of 24 telecommunications operators. On average, a firm in our sample had a stock of 593 patent applications in IRT and a stock of 1,251 patent applications in non-IRT; 4% of a firm's IRT stock were acquired, and 15% of firms were acquirers in a given year. Approximately one-third of our observations were characterized by mixed ownership. The average level of state ownership in our firm-year observations was 20%, and on average, 11 years had passed since the initial privatization. Regarding the other variables, an average operator invested 147 million EUR in R&D, had 15,177 million EUR in net sales, had a stock of 48 scientific publications, and had 43 million mobile, 12 million fixed-line, and 3 million broadband subscribers in its customer records.

[INSERT TABLE III ABOUT HERE]

Fig. 1 displays the evolution of the average patent stocks of our sample firms in IRT between 2000 and 2013. As can be seen, patent applications in digital technologies not only increased in total but also made up an increasing proportion of a firm's total patent stock. Over time, the total stock of patent applications in digital areas increased from approximately 300 in 2000 to 900 in 2013, and the share increased from 16% to 26%. This finding confirms that investments in digital technologies can be considered strategic from the perspective of telecommunications operators, and they are something on which future cash flows are likely to depend.

[INSERT FIGURE 1 ABOUT HERE]

Technology adoption

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Table IV presents our main set of regression results for testing Hypothesis 1. Column 1 reports the baseline estimates with control variables and year dummies. We find that firms with more scientific capabilities, those that invest more heavily in R&D and younger firms had a greater propensity to accumulate patent applications in IRT. Column 2 adds our dummy for mixed ownership. Including this variable substantially improves the overall fit of the model and significantly increases its explanatory power relative to the baseline model ($\chi^2 = 14.9$, $p < 0.01$). Specifically, we find that the coefficient estimate of mixed ownership is negative and significant ($p < 0.01$). The average partial effect, the mean of the marginal effects predicted for all of the observations of the sample, for the estimate of -0.749 implies that firms with mixed ownership are expected to have 70% lower investments in IRT (as proxied by patent applications stocks), compared to firms that are either fully private or in which the government owns a majority stake. As an initial proxy for unobserved firm-level factors, column 3 includes the pre-sample means of the dependent variable (which are highly significant), and these values increase the negative coefficient from -0.749 to -0.906. Further, we also obtain support for Hypothesis 1 when we use the share of state ownership and its squared term instead of a dummy variable capturing mixed ownership. In column 4, the coefficient estimate of the linear term is negative, while the quadratic term is positive, and both are significant at the 1% level, suggesting that responsiveness to discontinuous technological change is convexly negative in the share of state ownership. Partial or slow privatization might thus be particularly problematic when firms must adjust to technological discontinuities, a finding with implications discussed further in the conclusion.

Columns 5–7 present the first set of robustness tests for our main results. Column 5 reports OLS estimates in which the dependent variable is the natural logarithm of (one plus) the stock of IRT patent applications. Column 6 features the same independent variables but uses a GLM

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specification, in which the dependent variable is the share of the stock of IRT patent applications over the total stock of (ICT) patent applications. In both specifications, we find that the coefficients of mixed ownership remain significant. A potential concern with these results is that patenting might be driven by other reasons, such as deterring lawsuits, preventing others from blocking access to technologies, or enhancing a firm's bargaining position in licensing negotiations (Hall and Ziedonis, 2001). If the primary motives for patenting in IRT are driven by strategic concerns, it would compromise our interpretation of the estimated coefficients. To partially address such concerns, we weighted all of the patent-based measures by the number of forward citations – an approach frequently used to capture patent value (e.g., Pakes and Griliches, 1980; Griliches, 1981; Harhoff et al., 1999; Hall et al., 2005). The logic is that strategic patenting should attract fewer forward citations, as these patents have lower scientific value. To establish a comparable citation window, we apply a fixed 3-year window after publication and calculate the number of citations received. As shown in column 7, the coefficient estimate is considerably larger (i.e., more negative) when we use a citation-weighted count of the stock of IRT patent applications. Thus, it seems that our results are robust to this alternative interpretation.

[INSERT TABLE IV ABOUT HERE]

Selection issues

There might be concerns that the negative correlation between mixed ownership and adoption is driven by selection. The discussion of the determinants of privatization above suggests that this relationship is not likely; initial privatization decisions were made before the digital disruption affected the telecommunications industry, and the privatization decisions were made for reasons that are likely to be orthogonal to unobservable firm characteristics, which can be

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correlated with a firm's ability to respond to digitization. Nevertheless, as a second set of robustness tests, we consider an instrumental variable strategy based on the time passed since a firm's initial privatization. As discussed and empirically demonstrated in Borisova and Megginson (2011), the more years that have passed since the initial privatization, the higher the odds are that the state will further divest its ownership in a privatized firm. Moreover and for the reasons explained above, the time passed since the first privatization is unlikely to have a direct impact on the response to technological discontinuity in any intrinsic way, therefore making it a plausible instrument.

The first column of Table V presents the first stage, in which we regress mixed ownership on the number of years passed since a firm's initial privatization (and all of the other controls). Note that, since this instrument requires information about the first privatization year, we exclude operators that are not former state monopolies (e.g., Vodafone) from the analysis. As expected, the instrument is negative and highly significant. The first-stage *F*-statistic of the excluded instrument is greater than 10, which is the rule of thumb for weak instruments (Stock and Yogo, 2005), indicating that the instrument explains a sufficient part of the variation in mixed ownership. Column 2 presents estimates from the second-stage regression, in which we implement the instrumental variable estimator using the control function approach (see Blundell and Powell, 2004) because we use nonlinear count data models.[14] In column 3, we reproduce the main results of Table IV (column 3) to gauge the direction and magnitude of the bias (notice that the coefficients are slightly different before we drop 4 firms). Interestingly, the mixed ownership variable remains significant with a coefficient that is larger when controlling for unobservable factors. This bias could occur because of attenuation related to measurement error (less likely) or because the state retains some ownership in firms of higher quality (which could allow it to extract superior rents). At face value, this result suggests that we are underestimating

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the negative effect of mixed ownership on technology adoption by treating the ownership structure as exogenous.

Mode of adoption

Next, we investigate the channels through which operators make the transition to the digital space. As argued in Hypothesis 2, we expect that the mode of adoption via the acquisition of innovative target firms is more penalized by mixed ownership than internal developments. We could test the prediction in two separate count data models, but it is likely that the two dependent variables share contemporaneous error terms because both are derived from non-independent decisions; i.e., a company deciding to acquire external knowledge may simultaneously employ these two strategies. Thus, for our primary analysis, we use seemingly unrelated negative binomial (SUNB) models to examine operators' adjustment modes to digitization (Zellner, 1962). In additional tests, we provide GLM estimates, in which the dependent variable is replaced by the share of the stock of acquired IRT patents over the total stock of IRT patents and probit estimates using a dummy variable for whether a firm is an acquirer in a given year.

Panel B of Table V reports the regression results. First, we find that the coefficient estimates on mixed ownership are negative and statistically significant in columns 4 and 5, suggesting that mixed ownership hinders both vehicles of technology adoption to the digital landscape. We can also observe that the coefficient is more negative in column 4, the case of acquisitions, than in column 5, the case of internal development of digital technologies. In column 6, we confirm this finding when using as a dependent variable the share of the stock of acquired IRT patents over the total stock of IRT patents: firms with mixed ownership exhibit an even lower propensity to acquire external IRT than their counterparts. Finally, in column 7, we further show that mixed ownership reduces the likelihood of acquisitions more generally. While this

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evidence is consistent with the idea that acquisition decisions are particularly prone to ownership conflicts (as in Shleifer and Vishny, 1997; Bae et al., 2002), it also provides one explanation for why mixed owned firms are at such a disadvantage because external technology sourcing via acquisitions is an important channel to acquire the necessary capabilities for adoption during discontinuous technological change (Rothaermel, 2001; Puranam et al., 2006), but the enhanced risk of expropriation at the ownership level prevents managers from pursuing precisely this strategic option.

Firm market value

Finally, we provide one extension and investigate how an operator's response to digitization affects its market value. In particular, we ask whether financial markets reward the adoption of an innovation strategy in response to technological change. This approach assumes that current and potential investors recognize the need for a change in strategy and can infer it from patenting behaviors. The literature has shown that informed agents use all types of information sources (i.e., including patent records) available to them to assess a firm's innovation strategy and to forecast its future prospects. Their trading behaviors, in turn, have a significant impact on the price of firm stocks (e.g., Hall and Lerner, 2010; Aghion et al., 2013; Blanco and Wehrheim, 2017).

We estimate a version of the value function approach widely used in the literature (see, e.g., Griliches, 1981; Hall et al., 2005). The dependent variable is (the natural logarithm of) Tobin's Q, i.e., the ratio of a firm's market value to the replacement (book) value of its assets. A firm's market value is defined as the sum of the values of common stocks, preferred stocks, and total debt net of current assets. The book value of capital includes net plant, property and equipment, inventories, investments in unconsolidated subsidiaries, and intangibles other than R&D. We

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can separately account for the stock of a firm's IRT and non-IRT patent applications to test for any differences in their effects on firm value. To control for the quality of patent applications, we weight each application by the number of forward citations that it receives. In the empirical specification, we use OLS regressions with a slightly augmented set of control variables relative to our baseline specification (i.e., column 1 of Table IV). In particular, we employ the natural logarithm transformation of one-year lagged Tobin's Q as an additional explanatory variable to control for the dynamic nature of the technology adoption-performance relationship. This technique allows us to account for a potential dynamic panel bias (Zhou et al., 2014) and to nontrivially mitigate omitted variable biases (Wooldridge, 2010).

Panel C of Table V presents the estimation results. In column 8, we see that the stock of ICT-related patent applications is positively associated with market valuations ($p < 0.01$). Column 9 distinguishes between the stock of patent applications in IRT (digital) and the stock of patent applications in non-IRT (traditional telecommunications). We observe a positive and significant coefficient for innovation efforts in the digital space. The coefficient of 0.009 suggests that an 8.8 percentage point increase in IRT (i.e., roughly the compounded annual growth rate) is associated with an increase in Tobin's Q of approximately 8% the following year. In contrast, the estimated coefficient of non-IRT implies a marginal effect close to zero. In summary, the estimates are in line with the view that the financial market rewards operators' innovative efforts in the digital space.

[INSERT TABLE V ABOUT HERE]

6. Discussion and conclusion

In this paper, we theorize and test whether firms with mixed ownership, i.e., firms with shares partly privately held and partly held by the government, are less responsive to technological

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discontinuities. We posit that the reason for sluggish responses is that top management is subject to conflicting views about how the corporation should address the challenges arising from technological change, thereby making it more likely to maintain the status quo. Our context consists of European telecommunications operators and their responses to digitization. We find that telecommunications operators with mixed ownership have significantly fewer digital patent applications in their portfolios than companies that are fully privately owned or companies in which the government holds a majority stake. This main result persists after considering quality-weighted measures, alternative econometric models, selection issues, and a quadratic model of government ownership, providing another comparable perspective on its association with technology adoption. To identify the mechanism, we examine the mode of adoption of digitization and find that internal conflicts are more of a hindrance to acquisition decisions. To take a step further toward a normative conclusion, we also show that financial market participants reward patenting in the digital space with higher market valuations.

The study presented here, like any other, has limitations, indicating some potential avenues for future research. The size of our dataset (although it contains nearly all of the incumbent operators within the European telecommunications industry) renders some analyses problematic to perform and interpret. In addition, our choice of the research context limits the types of questions that these data are suited to address. As emphasized in several studies, technological change can take multiple forms, and the introduction of digital technologies for telecommunications companies represents one specific change within a single industry. While digitization as a disruptive innovation can well be regarded as a broader phenomenon, it does not necessarily affect all industries in the same way. In our case, for instance, the customers of the old and the new telecommunications technologies are largely identical; thus, we can say

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little about situations such as those discussed by Christensen and Bower (1996), in which emerging technologies would initially target a different customer niche.

Although patent data are an appealing and easily accessible measure of firms' innovative outcomes in the digital space, classifying patents according to their patent classification can result in false positives and negatives. However, this error is less of a concern in some classes, such as IPC class H04L, 'transmission of digital information', which includes, for example, Deutsche Telekom's patent applications for cashless payment transactions using a mobile terminal (see, e.g., EP2626824). We acknowledge that some classes can be more heterogenous than others since patent classifications must bring together diverse sets of technologies. However, the feedback from industry experts confirmed that the classification used throughout this study allows for a reasonably clear and precise operationalization of technology areas, which is crucial to obtain comparable quantitative measures across firms and over time. Thus, at least for our purposes, patent data might be the best measure available.

Despite these limitations, this research has some interesting implications for understanding incumbents' response patterns in the face of discontinuous technological change. The documented systematic association between mixed ownership and a firm's response to digitization indicates that the ownership structure is an important and overlooked source of heterogeneity across firms in the face of discontinuous technological change. Extant theories and empirical evidence would explain differences in firm adaptation using arguments about incentives and/or evolutionary views about capabilities, routines or awareness. In the telecommunications industry, however, digitization has been sweeping, and the question of awareness should therefore be of little relevance. Moreover, our analysis suggests that a lack of resources and capabilities is unlikely to be the dominant reason for a sluggish response. Instead, our findings are in line with Eggers and Kaplan (2009), who suggested that 'cognitive blinders'

Tesi di dottorato "Essays on Corporate Science and Technological Change"
di DALAY HAKKI DOGAN
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play a crucial role in shaping the response to discontinuous technological change. We complement their findings by showing that such blinders have their origin not only at the managerial level but also at the organizational (governance) level.

In terms of policy implications, our research shows that privatization decisions significantly influence a firm's responsiveness to technological change because we find that the effect of mixed ownership is both statistically and economically meaningful. This finding suggests that the privatization process leads to uncertainties over the control and direction of the company, consistent with prior research that documented higher credit spreads for partially privatized firms (Borisova and Megginson, 2011). This turmoil would disappear were the government to completely release a firm or maintain solid controlling ownership of a company. While it is, of course, possible that such equity reductions are positive in terms of private and social interests, our findings emphasize the potential consequences when exogenous technological change occurs. As such, our study speaks indirectly to the advantages of speedy full divestiture, at least in highly volatile, technology-intensive industries. Given the large number of state-owned companies that remain to be privatized and the persistence of substantial government ownership after privatization (see, e.g., Bortolotti and Faccio, 2009), our results might be relevant to the decision-making processes of managers, investors, and governments.

Tesi di dottorato "Essays on Corporate Science and Technological Change"
di DALAY HAKKI DOGAN
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Notes

1 Various factors explain incumbents' sluggish responses to discontinuous technological change. Scholars have pointed to the role of organizational inertia (Tripsas, 2009), a lack of capabilities and/or economic incentives (Henderson, 1993; Teece et al., 1997), low resource commitment (Christensen, 1997), a lack of attention (Kammerlander and Ganter, 2015), and top management's cognitive inertia (Hill and Rothaermel, 2003; Kaplan, 2008).

2 Indeed, the existing evidence has suggested that firms fail to adjust not because of their inability to amass the required resources and competences but because their top management is affected by cognitive biases and behavioral inertia, which often paralyze their decision making (Hill and Rothaermel, 2003; Kaplan, 2008; Tripsas and Gavetti, 2000; Eggers and Kaplan, 2009).

3 In a quite different context, Borisova and Megginson (2011) showed that mixed enterprises that are the outcomes of privatization processes experience higher credit spreads than public companies. However, credit spreads are lowest for fully privatized firms.

4 Note that the advent of VoIP as a radical technological discontinuity has been used in studies by Benner (2010) and Benner and Ranganathan (2013).

5 Examples include: 'Internet Phone Service Threatens Industry's Giants' (The Wall Street Journal, 2003), 'How the internet killed the phone business' (The Economist, 2005), 'Drop in texting heralds industry shift' (Financial Times, 2012), 'IP technology disrupts voice telephony' (Flanagan, 2012) or 'Telecom companies count $386 billion in lost revenue to Skype, WhatsApp, others' (Fortune, 2014).

6 See http://www.btplc.com.

7 For other studies that used patents as indicators of innovation in a similar setting, see, e.g., Dosi et al. (2006) and Corrocher et al. (2007).

8 M&A data allowed us not only to account for changes in business groups over the period between 2000 and 2013 but also helped us to reconstruct ownership links to affiliates that dissolved prior to 2000 and fully integrate them into the parent company.

9 Compared to approximate string matching, the advantage of this conservative method lies in a high level of precision at the expense of some loss of completeness. As a first step,

Tesi di dottorato "Essays on Corporate Science and Technological Change"
di DALAY HAKKI DOGAN
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company and assignee names were standardized following the steps proposed by Magerman et al. (2006). The main standardization procedures involved in this study covered the following categories: character cleaning; punctuation cleaning (preparsing); legal form indication treatment; spelling variation standardization; condensing; and umlaut standardization. In a second step, we matched the sample firms with the list of the harmonized patent assignee names.

10 The EPO classifies all patents into at least one technology field using the IPC System, which classifies the technology landscape into 639 IPC four-digit subclasses (IPC classification version 2017.01 was used in this study) and tens of thousands of main groups and subgroups nested within these sub-classes (see WIPO, 2017).

11 Note that alternative cutoff values of 5% or 10% yield similar results.

12 Although the computation of the stock variables is technically straightforward, assumptions must be made regarding the initial stocks, which remain partly unobserved. In our study, we applied a standardized growth rate (g) for R&D and other knowledge stock measures of 8% since our sample consisted only of high-technology firms (see, e.g., Hall and Oriani, 2006). In formal terms, the initial R&D stock, for example, is approximated as follows: R&D $\text{stock}_{it0} = \text{R\&D}_{it0}/(\delta + g)$.

13 We implement their solution using Stata's 'generalized linear models' (GLM) command with a Bernoulli variance function and a logit link function – a standard approach for coping with fractional dependent variables.

14 We also considered standard 2SLS as an alternative to the control function. The coefficient (standard error) on mixed ownership in the 2SLS estimation was also greater than the OLS estimate: 3.113 (1.264).

Tesi di dottorato "Essays on Corporate Science and Technological Change"
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Figures

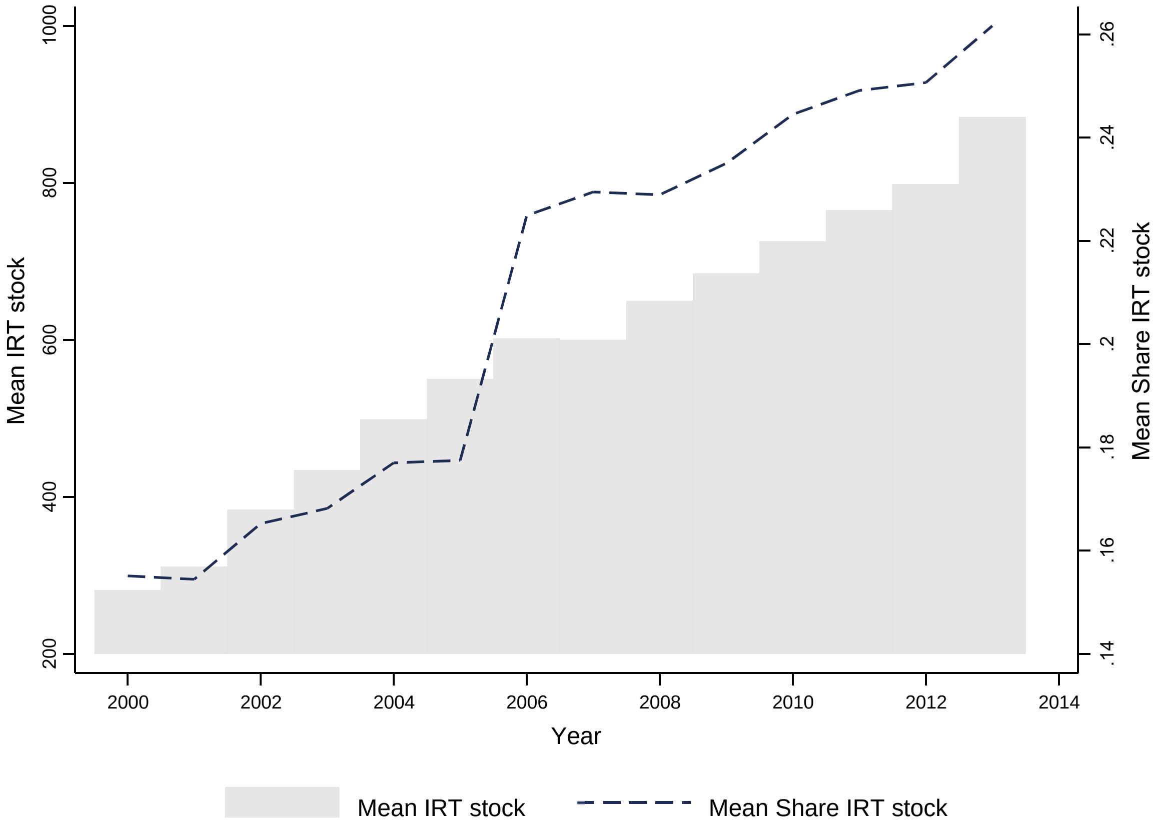

Fig. 1. Telecommunications operators' patent portfolios in Internet-related telecommunications technologies (IRTs). The figure presents the average annual patent stock in IRT both in absolute terms and as a share of firms' total patent stocks in information and communication technologies.

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Tables

Table I
Telecommunications company sample.

Company	Country	Year of full liberalization	Year of privatization	Years in the sample
Deutsche Telekom	Germany	1998	1996	2000–2013
Vodafone	United Kingdom	1991	n/a	2000–2013
Telefonica	Spain	1998	1987	2000–2013
France Telecom	France	1998	1997	2000–2013
BT	United Kingdom	1991	1984	2000–2013
Telecom Italia	Italy	1998	1997	2000–2013
Telenor	Norway	1998	2000	2000–2013
Swisscom	Switzerland	1998	1997	2000–2013
TeliaSonera	Sweden	1993	2000	2000–2013
KPN	Netherlands	1997	1994	2000–2013
Belgacom	Belgium	1998	1996	2003–2013
Turk Telekom	Turkey	2003	2005	2007–2013
Telekom Austria	Austria	1998	1998	2000–2013
OTE	Greece	2001	1996	2000–2013
Turkcell	Turkey	2003	n/a	2007–2013
Tele2	Sweden	1993	n/a	2000–2013

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TDC	Denmark	1996	1994	2000–2013
Telekomunikacja Polska	Poland	2001	1998	2001–2013
Magyar Telekom	Hungary	2001	1993	2000–2013
Eircom	Ireland	1998	1999	2000–2005
Elisa	Finland	1994	n/a	2000–2013
Cesky Telecom	Czech Republic	2000	1994	2000–2013
Telekom Slovenije	Slovenia	2001	1998	2006–2013
Portugal Telecom	Portugal	2000	1995	2000-2012

Table II

ICT-relevant technological classes.

Technology field	IPC code
Internet-related telecom	G06F, G06N, G09F, H04K, H04L
Traditional telecom and	A63F, B23K, B29C, G01R, G01S, G03B, G06K, G06Q,
other ICT-related classes	G06T, G07G, G08C, G10L, H01B, H01H, H01P, H01Q, H01R, H02B, H02G, H03H, H03K, H03L, H03M, H04B, H04H, H04J, H04M, H04N, H04Q, H04W, H05K, H94R

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Table III
Descriptive statistics.

	Mean	StdDev	Min	Max	Observation
Mixed ownership	0.32		0	1	303
State ownership	0.20	0.24	0	0.79	303
Length initial privatization (in years)	11.4	5.7	0	29	254
IRT application stock	592.6	1,094	0	6,221	303
Non-IRT application stock	1,251	1,920	0	8,739	303
Share of IRT stock acquired	0.04	0.07	0	0.33	303
Acquiror	0.15		0	1	303
R&D (in EURm)	146.6	270.6	0	1,900	303
Sales (in EURm)	15,177	17,961	441.5	64,602	303
Firm age (in years)	32.8	35.7	3	132	303
Tobin’s Q	1.4	0.37	0.68	3.2	263
Scientific publication stock	48.4	119.2	0	684.4	303
Fixed-line subs. (in m)	11.5	14.6	0	56.9	303
Broadband subs. (in m)	3.0	4.6	0	18.6	303
Mobile subs. (in m)	43.1	70.61	0	434.1	303

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Table IV Mixed ownership and technology adoption. N = 303. Firms in columns: 24. Estimation period is 2000–2013. Robust standard errors are reported in parentheses. All regressions control for a full set of time dummies. BGV effects are presample means of the dependent variable, as proposed by Blundell, Griffith, and Van Reenen (1999). $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Estimation method	Negative binomial	Neg. binomial	Neg. binomial	Neg. binomial	OLS	GLM	Neg. binomial
Dependent variable	IRT stock	IRT stock	IRT stock	IRT stock	Ln(IRT stock)	IRT share	IRT Cites
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Mixed ownership		-0.749***	-0.906		-0.634***	-0.684***	-1.586***
		(0.194)	(0.133)		(0.108)	(0.174)	(0.229)
State ownership				-4.533***			
				(0.970)			
State ownership2				6.849***			
				(1.755)			
Ln(R&D stock)	0.673***	0.660***	0.280***	0.274***	0.198***	0.198***	0.456***
	(0.054)	(0.057)	(0.037)	(0.040)	(0.038)	(0.051)	(0.053)
Ln(Sale)	0.408*	0.193	-0.002	-0.008	0.071	-0.271	0.235
	(0.209)	(0.204)	(0.101)	(0.106)	(0.128)	(0.188)	(0.165)
Ln(Firm age)	-0.421***	-0.434***	-0.330***	-0.340***	-0.280***	-0.039	-0.189
	(0.129)	(0.133)	(0.080)	(0.088)	(0.072)	(0.107)	(0.155)
Ln(Publications stock)	0.643***	0.660***	0.146**	0.171***	0.127***	0.345***	0.186***
	(0.087)	(0.086)	(0.063)	(0.060)	(0.048)	(0.086)	(0.069)
Ln(# of fixed-line subs)	-0.459***	-0.375***	-0.495***	-0.558***	-0.519***	-0.198*	-0.418***
	(0.133)	(0.137)	(0.086)	(0.086)	(0.096)	(0.115)	(0.125)
Ln(# of broadband subs.)	-0.435*	-0.217	0.250*	0.235*	0.436**	0.204	0.424*
	(0.251)	(0.268)	(0.138)	(0.139)	(0.175)	(0.182)	(0.223)
Ln(# of mobile subs.)	-0.263***	-0.142	0.425***	0.409***	0.295***	0.071	0.241**
	(0.097)	(0.103)	(0.047)	(0.047)	(0.044)	(0.063)	(0.101)
BGV effects	No	No	Yes***	Yes***	Yes***	Yes***	Yes***

Tesi di dottorato "Essays on Corporate Science and Technological Change"
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Table V

Mixed ownership, selection issues, modes of technology adoption and firm market value.

Estimation period is 2000–2013. Robust standard errors are reported in parentheses. All regressions control for a full set of time dummies. The regressions in panels A and B include presample means of the dependent variable as proposed by Blundell, Griffith, and Van Reenen (1999). * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

	Panel A: Endogeneity issues			Panel B: Internal vs. external research				Panel C: Firm market value	
Estimation method	Probit	NBREG	NBREG	SUNB	SUNB	GLM	Probit	OLS	
Dependent variable	Mixed Ownership	IRT stock	IRT stock	IRT apps acquired	IRT apps internal	IRT share acquired	Acquirer	Ln(Tobin's Q_{t+1})	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Length of initial privatization	-0.129*** (0.034)								
Mixed ownership (instr.)		-1.032*** (0.143)							
Mixed ownership			-0.867*** (0.150)	-1.648*** (0.235)	-0.896*** (0.132)	-0.316** (0.158)	-0.404** (0.188)		
Ln(ICT stock)								0.008** (0.003)	
Ln(IRT stock)									0.009** (0.004)
Ln(Non-IRT stock)									-0.002 (0.005)

Tesi di dottorato "Essays on Corporate Science and Technological Change"
di DALAY HAKKI DOGAN
discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2020
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Sono comunque fatti salvi i diritti dell'università Commerciale Luigi Bocconi di riproduzione per scopi di ricerca e didattici, con citazione della fonte.

Ln(Tobin's Q)								0.707***	0.705***
								(0.046)	(0.046)
Ln(R&D stock)	-0.089	0.366***	0.284***	0.334***	0.279***	0.490***	0.087*	-0.005	-0.003
	(0.064)	(0.042)	(0.038)	(0.123)	(0.037)	(0.118)	(0.049)	(0.004)	(0.004)
Ln(Sale)	-1.391***	2.107***	-0.554**	0.482*	-0.002	0.951**	0.224	-0.002	-0.002
	(0.396)	(0.354)	(0.245)	(0.267)	(0.102)	(0.391)	(0.208)	(0.013)	(0.013)
Ln(Firm age)	0.422***	-0.521***	-0.398***	-1.140***	-0.307***	-1.582***	-0.085	0.015**	0.020***
	(0.135)	(0.072)	(0.083)	(0.310)	(0.081)	(0.213)	(0.118)	(0.006)	(0.007)
Ln(Publications stock)	-0.002	0.229***	0.188***	-1.144***	0.189***	-1.492***	0.099	0.006	0.007
	(0.106)	(0.075)	(0.066)	(0.100)	(0.065)	(0.164)	(0.079)	(0.005)	(0.005)
Ln(# of fixed-line subs.)	1.219***	-1.749***	-0.177	0.402***	-0.525***	0.919***	-0.436***	0.002	-0.001
	(0.260)	(0.197)	(0.154)	(0.153)	(0.086)	(0.184)	(0.161)	(0.009)	(0.009)
Ln(# of broadband subs.)	-0.114	0.651***	0.662***	0.265	0.249*	-0.405	0.356	-0.017	-0.017
	(0.316)	(0.175)	(0.208)	(0.224)	(0.140)	(0.251)	(0.254)	(0.016)	(0.016)
Ln(# of mobile subs.)	1.094***	-1.320***	0.477***	0.556***	0.414***	-0.208**	0.002	-0.006	-0.005
	(0.254)	(0.211)	(0.058)	(0.096)	(0.048)	(0.105)	(0.092)	(0.007)	(0.007)
IV Test		$F = 14.46$ ($p < 0.01$)							
N	254	254	254	303	303	303	303	263	263
# of firms	20	20	20	24	24	24	24	24	24

Tesi di dottorato "Essays on Corporate Science and Technological Change"
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Table A.I

Additional robustness test (Appendix). Estimation period is 2000–2013. Robust standard errors are clustered at the firm level. All of the regressions control for a full set of time dummies and presample means of the dependent variable, as proposed by Blundell, Griffith, and Van Reenen (1999). $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	Panel A (Models 1-4): Huber-White robust clustered s.e.				Panel B (Models 5-6): Wild bootstrap clustered s.e.	
Estimation	NBREG	NBREG	OLS	OLS	OLS	OLS
Dependent variable	IRT stock	IRT stock	Ln(IRT stock)	Ln(IRT stock)	Ln(IRT stock)	Ln(IRT stock)
	(1)	(2)	(3)	(4)	(5)	(6)
Mixed ownership	-0.906***		-0.634**		-0.634**	
	(0.314)		(0.254)		(0.259)	
Mixed ownership *(instr.)*		-1.032***		-0.812***		-0.812*
		(0.338)		(0.248)		(0.445)
Ln(R&D stock)	0.280***	0.366***	0.198**	0.228**	0.198**	0.228*
	(0.072)	(0.113)	(0.077)	(0.091)	(0.088)	(0.138)
Ln(Sale)	-0.002	2.107**	0.071	1.360	0.071	1.360
	(0.230)	(0.987)	(0.237)	(0.970)	(0.435)	(1.349)
Ln(Firm age)	-0.330*	-0.521***	-0.280*	-0.334*	-0.280	-0.334
	(0.178)	(0.175)	(0.157)	(0.166)	(0.205)	(0.217)
Ln(Publication stock)	0.146	0.229	0.127	0.297**	0.127	0.297**
	(0.162)	(0.217)	(0.110)	(0.103)	(0.127)	(0.147)
Ln(# of fixed-line subs.)	-0.495***	-1.749***	-0.519***	-1.391***	-0.519**	-1.391**
	(0.154)	(0.513)	(0.155)	(0.386)	(0.245)	(0.566)
Ln(# of broadband subs.)	0.250	0.651***	0.436	0.830**	0.436	0.830**
	(0.211)	(0.233)	(0.291)	(0.284)	(0.402)	(0.318)
Ln(# of mobile subs.)	0.425***	-1.320**	0.295**	-0.819	0.295**	-0.819
	(0.119)	(0.627)	(0.109)	(0.572)	(0.139)	(0.805)
N	303	254	303	254	303	254
# of firms	24	20	24	20	24	20

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Science in Times of Turbulence – Evidence from Pharmaceutical Industry

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Abstract

We study the relationship between science and technology in the aftermath of a technological change. We argue that the substitution of internal scientific efforts with external knowledge sourcing may leave firms unprepared for discontinuous technological changes. As firms become increasingly reliant on external scientific knowledge, their in-house science and technology assets fail to help them when there is a technological discontinuity. By putting together data on acquisition events in the global pharmaceutical industry, we study the importance of in-house science and technology in response to the combinatorial chemistry revolution in the pharmaceutical industry. Using data on cumulative abnormal returns, we find that targets with stronger scientific capabilities generate higher abnormal returns for the acquirors pursuing them. We interpret this finding as evidence that the value of science increases after a technological change.

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Introduction

Strategy literature has documented the importance of complementarities between different knowledge sources in facilitating innovation (Karim and Mitchell, 2000; Cassiman and Veugelers, 2006; Makri, Hitt, and Lane, 2010). Despite the existence of strong synergies from tapping into internal and external knowledge sources, companies seem to use external acquisition of knowledge increasingly as a substitute to engaging in R&D efforts by themselves. This trend is most notable in corporate scientific efforts: U.S. companies active in manufacturing sector have been putting less emphasis on internal scientific efforts, even though their emphasis on development broadly remains the same (Arora et al. 2018). The authors broadly attribute this trend to the fact that companies are increasingly becoming more able to efficiently outsource these efforts. It seems that if you can buy it, you don't need to produce all the knowledge yourself. This leads to an immediate question: Can firms afford to decrease investments in internal scientific efforts in the long run?

In this paper, we build on the notion that the ability of the companies to source new scientific knowledge from outside of the firm is a double-edged sword. On the one hand, tapping into external scientific knowledge allows firms to avoid some of the costly and long-term projects shrouded in uncertainty with more in-house scientific workers. On the other hand, becoming too reliant on an external supply of scientific knowledge leads to a mid-to-long-term challenge of sustainable supply of new ideas and the ability to assimilate these new ideas. Here we propose that the relationship between technology and science has a changing nature. While tapping into external scientific knowledge can substitute in-house development of science in the absence of technological changes, without an adequate level of in-house scientific investment, it becomes too difficult for firms to navigate the increasing uncertainties emerging from a technological discontinuity. We contend that the substitution of internal science by the

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external, forces firms to become even more reliant on external sourcing when new technologies emerge. As firms lose their ability to assess how to develop the new capabilities to navigate the technological discontinuity, they end up relying on the acquisition of knowledge from the outside. We test our arguments in the U.S pharmaceutical industry throughout 1990s, which was subject to a discontinuous technological change in middle of 1990s with the emergence of combinatorial chemistry and high output screening affecting the entire industry (Thomke and Kuemmeler, 2002; Asgari, Singh, and Mitchell, 2017). Our initial findings provide preliminary support for some of our theoretical conjectures.

Theoretical Framework

Science allows technology to be less firm-specific as experiments can be better understood in the context of abstract, universal theory, instead of firm specific environments (Arora and Gambardella, 1994a). Representation of knowledge in abstract and general terms allows for the use of that knowledge in locations that are distant from the source. As science is an abstract scheme of evaluating what is useful in the innovative process, the implication is that technical advance, once scientifically motivated, is divisible, transferrable and tradable. Once everyone can understand the scientific grounds on which experiments lie, their contribution can be more easily valued and their validity can be assessed (Rosenberg, 1990; Arora and Gambardella, 1994b). Furthermore, science allows for the accumulation of technical knowledge to be separated from firm size. In the absence of science, technical knowledge accumulates over time and cannot be transferred across firms due to a lack of the ability to evaluate information. Thus, in the absence of science, larger and older firms — firms with lots of accumulated experimentation — have an advantage over smaller and de-novo firms. With investments in science, firms no longer have to learn from their own cumulative experimentation, as they can also learn from that of other firms (Arora, Fosfuri, Gambardella, 2001). By breaking up the link

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between firm size and technical advance, science leads to greater efficiency in technology development achieved by specialization in different parts of innovative value chain. Despite these benefits of science for the accumulation and advance of technology, findings of Arora et al. (2018) indicate “a decline in the number of publications by US corporations over time and a drop in the value of existing scientific capability.” Among the alternative explanations considered, the authors interpret their finding as a result of the declining value of scientific capabilities, instead of a drop in the value of internal research or an increase in the cost of internal research. As firms don’t need to develop the scientific capabilities themselves, they substitute their internal efforts with external knowledge.

> H1: In the absence of a technological discontinuity, firms with lower amount of scientific assets create more value from acquiring targets with scientific assets, as opposed to those with a higher amount of scientific assets.

Management scholars have been pointing to the importance of developing the ability to acquire and assimilate new knowledge within the firm (Cohen and Levinthal, 1989; Zahra and George 2002). A technological discontinuity offers major price-performance increases that despite adjustments to scale, efficiency or design, existing technologies cannot compete in the new regime (Tushman and Anderson, 1986). Firms obtaining scientific investments can move to the frontier of the changes, or develop the capabilities required to act in the new regime, in the aftermath of competence destroying changes (Rosenberg, 1990; Pavitt, 1991). This when incumbent firms need to acquire, and successfully assimilate new knowledge in order to adopt to the new technological regime. The growing distance of corporations to scientific knowledge and increasing reliance on external acquisition of this knowledge, makes firms without scientific investments vulnerable. Acquiring knowledge from outside plays a key role in adopting to change, as external knowledge allows to reconfigure the firm to the new environment by bringing different resources and building on the existing ones (Karim and

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Mitchell, 2000). When relying on external knowledge to build scientific capabilities, the increasing complexity of the knowledge during technological change, makes it difficult to identify what is necessary to adopt to the new regime and which of the internal resources can build on the new ones. Furthermore, even when firms acquire scientific knowledge, they may not end up integrating the acquired science into their technologies, as they cannot identify the type of science they need before the deal. Indeed, acquiring the wrong resources can lead to tensions within the organization loss of valuable resources, besides the obvious failure to develop the necessary capabilities. This implies that firms without scientific capabilities fail to benefit from the new knowledge they obtain by acquiring science-based targets. All of these arguments indicate that internal science is necessary to build on the external knowledge inputs.

> H2: In times of technological discontinuity, complementing internal science with external science leads to higher returns from acquisitions.

Data & Setting

We choose pharmaceuticals industry as the testing bed of our hypotheses. Pharmaceutical industry was subject to a discontinuous transformation in mid-1990s. Starting from 1986, new methods to discover new drugs were emerging in what became later known as combinatorial chemistry revolution (Thomke and Kuemmerle, 2002). These new efforts in chemistry drastically took off in year 1995, and peaked for the two years immediately after (Asgari, Singh, Mitchell, 2017; Persidis, 1998; Thomke and Kuemmerle, 2002). Combinatorial chemistry greatly simplified and allowed to scale up the search for new drugs by generating computer aided visualizations for possible drug candidates. The effect of combinatorial chemistry on the competitiveness of firms has been documented (Thomke, Von Hippel, and Franke, 1998). This transformation was largely exogenous to biopharmaceutical industry, as it emerged from the

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efforts of academic researchers (Asgari et al., 2017). This setting provides an interesting set-up to test our theory for several reasons: First, the combinatorial chemistry is an exogenous event that alters the basis of knowledge and the competences required to stay competitive without switching to the new technology (Anderson and Tushman, 1986). Second, pharmaceutical industry is traditionally a scientifically driven industry (Sears and Hoetker, 2014). As we are interested in observing the changes in the importance of science in the aftermath of a technological discontinuity, pharmaceutical industry throughout 1990s provides an ideal setting to test our theory.

To test our theory, we bring together data from several different sources. Following the earlier literature, we focus on pharmaceutical industry based on the 3-digit SIC code of 283 (Kale, Dyer and Singh, 2002). We refer to Compustat database for basic information on companies active in the pharmaceutical industry. For the companies we identify as active in the pharmaceutical industry, we check their merger and acquisition activity from the SDC Platinum database for a window of 5 years before and after the starting year of the combinatorial chemistry revolution. We identify 308 firms that are involved in at least one acquisition deal and 289 firms that are not active in M&A events throughout our study period of 1990-2000 from the pharmaceutical industry. For the firms active in the M&A space, we identify 959 deals and gather information on these deals from the SDC Platinum database. As we are interested in the stock market reaction to the M&A event, we restrict our attention to an event window around the time of announcement, and the deals with available information on the stock returns.

We follow a recent study by Kogan et al. (2017) and collect patents data on the sample firms from the NBER patent dataset. Following Arora et al. (2018), we also compile the scientific publications of the firms in our sample from Web of Science to measure the scientific capabilities of the acquiror firms, non-acquiror firms as well as targets. We develop three

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measures for the scientific and inventive capabilities, whether the firm is active in patenting and publishing activities in a window of the past 5 years, and in the past 3 years. Following Hall, Jaffe, and Trajtenberg (2005) we also use discounted measures of the total stocks of patents and publications of the acquirors and the targets, with a discount factor of 0.15 for every year that has passed since the year of publication and the year of filing for a patent.

Finally, we use an event study methodology (McWilliams and Siegel, 1997; Oxley, Sampson and Silverman, 2009), which requires calculating "normal" returns for a company over a window of time. Following Oxley et al. (2009), we use an estimation window of 150 days starting from -170 working days to -21 working days before the announcement date of the event. Around the announcement date, we use three different event windows to calculate the cumulative abnormal returns. We calculate cumulative abnormal returns for an event window of 2 days (-1,0), 3 days (-1,+1), and 7 days (-3,+3) around the time of announcement. An important issue then is to avoid the possibility that some information about the deal may become available to the public about the possibility of a deal before the deal is actually announced. Following Muhlerin and Simsir (2015), we use "Original Date Announced" variable of SDC Platinum tracking the first mention of the event in the public space, to identify the date of announcement of the acquisition event. This mitigates some of the concerns regarding the early availability of information in media and rumors pertaining to the deal. For the observations during the estimation window of 150 days, we use the S&P 500 value weighted index to predict the actual returns of the company's stock during the estimation window. This variable is collected from the CRSP database of Wharton Research Data Services. In the below equation, r_{it} stands for the daily return for firm i on day t, r_{mt} stands for the daily return for the value-weighted S&P 500, α_i and β_i are firm-specific coefficients, and ε_{it} is an independently and identically distributed error term:

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$$r_{it} = \alpha_i + \beta_i \, r_{mt} + \varepsilon_{it}$$

After we obtain the predicted returns based on the value weighted market index, we have a measure of the normal returns for each company. We subtract the predicted normal returns from the realized returns of the company stock for each day in our three different time windows around the announcement date of the acquisition event, thereby obtaining the cumulative abnormal returns for each day around the announcement date. This is our main dependent variable in the analyses.

In follow-up analyses, we also plan to include a comparison between two industries where science is of key importance by adding chemicals industry as well. Furthermore, we also expect to use another industry where science is not a key input in innovation, to show the across industry variation in the effect we observe in this study. An important limitation of our approach is that we have not yet taken into account possible confounding events around the deals. As noted by McWilliams and Siegel (1997) and Sears and Hoetker (2014), this is a crucial consideration as other events may cause noise interfering with the interpretation of cumulative abnormal returns. Please see Table 1 below in the Appendix, which reports the descriptive statistics for the main variables used in the analyses below, as well as variable descriptions.

[Insert Table 1 about here.]

Analysis and Results

We carry out our analyses by using a dependent variable that allows for a deal to be included in the analysis if the acquiror stock is available for as few as 10 days within our 150-day estimation window. We first check that the cumulative abnormal returns measures we calculate are statistically different from 0. In Table 2 below, we see that the constant from the regression is significant, thereby indicating that the cumulative abnormal returns for the 2-day, 3-day and

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7-day event windows that we use in our main regressions as the dependent variable, are statistically significantly different from 0.

Table 2

VARIABLES	(1) car _2day	(2) car _3day	(3) car_7day
Constant	0.00827***	0.0110***	0.0176***
	(0.00260)	(0.00326)	(0.00437)
Observations	875	875	875
R-squared	0.000	0.000	0.000

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

We start by reporting the results of a regression where we use a dummy variable that assumes the value of 0 before the technological change (before 1995), and the value of 1 in the aftermath of the technological change between 1995 to 2000 (inclusive). Even though we have 966 observations in our test bed, we lose 91 observations due to the limited availability of stock information for the acquiror firms, which is crucial for the dependent variable.

Table 3

VARIABLES	(1) car_2day	(2) car_3day	(3) car_7day
post_shock	-0.00432	-0.00901	-0.0139
	(0.00497)	(0.00675)	(0.00941)
Constant	0.0112***	0.0171***	0.0270***
	(0.00358)	(0.00538)	(0.00779)
Observations	875	875	875
R-squared	0.001	0.002	0.003

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

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The results of the regression indicate that the cumulative abnormal returns resulting from deals announced after the technological shock are not meaningfully different than the cumulative abnormal returns before the technological regime change.

	Table 4a			Table 4b		
	(1)	(2)	(3)	(4)	(5)	(6)
Variables	car_2day	car_3day	car_7day	car_2day	car_3day	car_7day
Constant	0.00687**	0.00810**	0.0131**	0.0112***	0.0171***	0.0270***
	(0.00345)	(0.00407)	(0.00528)	(0.00358)	(0.00538)	(0.00779)
N	590	590	590	285	285	285
R-squared	0	0	0	0	0	0

Robust standard errors are in parantheses *** p<0.01, ** p<0.05, *p<0.1

Nonetheless, results in Table 4a indicate that, when we constrain the analysis to the deals in the post period (with the remaining observations being in the pre-period in panel b of Table 4) the cumulative abnormal returns are still positive and statistically significantly different from 0.

Table 5

	(1)	(2)	(3)
VARIABLES	car_2day	car_3day	car_7day
pharma_dummy	0.0116**	0.0129**	0.0186**
	(0.00519)	(0.00654)	(0.00876)
Constant	0.00263	0.00476	0.00857
	(0.00362)	(0.00411)	(0.00572)
Observations	875	875	875
R-squared	0.006	0.004	0.005

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Next, we report the results of a regression where the dependent variable is the cumulative abnormal returns from different event windows and the independent variable is a dummy

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variable assuming the value of 1 when the target firm is a pharmaceutical company (3 digit sic code of 283). In our final testing bed of 875 observations, 448 of the deals feature a target that has a primary sic code from outside of pharmaceutical industry, while 427 deals feature targets have primary sic codes from pharmaceutical industry. We observe that deals involving pharma targets generate higher cumulative abnormal returns compared to deals involving targets from outside of pharmaceutical industry.

	Table 6a			Table 6b		
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	car_2day	car_3day	car_7day	car_2day	car_3day	car_7day
target_pub_stock	-7.77e-06	-2.17e-05	-3.81e-05	8.49e-05	8.12e-05	0.000109
	(2.43e-05)	(2.35e-05)	(2.98e-05)	(5.41e-05)	(5.87e-05)	(7.06e-05)
acquiror_pub_stock	-1.25e-05	-2.20e-05**	-3.89e-05***	-1.52e-06	-8.39e-06	-1.02e-05
	(7.77e-06)	(1.04e-05)	(1.43e-05)	(5.85e-06)	(7.19e-06)	(8.95e-06)
pub_stock_interact	-2.39e-08	1.23e-08	7.26e-08*	-4.10e-08	-3.27e-08	-1.26e-07
	(3.72e-08)	(3.62e-08)	(3.86e-08)	(7.09e-08)	(7.79e-08)	(9.32e-08)
Constant	0.0133***	0.0209***	0.0335***	0.00487	0.00708	0.0122**
	(0.00435)	(0.00666)	(0.00965)	(0.00388)	(0.00468)	(0.00606)
Observations	285	285	285	590	590	590
R-squared	0.006	0.007	0.009	0.014	0.010	0.010

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

In Table 6a and 6b, we present our first findings on our theory. Our theory predicts that acquirors with a higher amount of scientific assets will generate lower returns from acquiring targets with scientific assets, in the absence of a technological discontinuity, compared to when a technological discontinuity is present. From panel a of Table 6, we observe that while the interaction of the publication stocks of targets and acquirors is insignificant in model 1 and model 2, it is positive and significant in model 3, where we also observe a negative effect of acquirors' publication stocks on the umulative abnormal returns from the deal. This is in

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contrast to the analogous models of 4,5, and 6, where the analysis is restricted to the post deals, and no effect of the interaction variable is present. We interpret this finding as supportive evidence for hypothesis 1.

Table 7

VARIABLES	(1) car_2day	(2) car_3day	(3) car_7day
post_shock	-0.0112	-0.0144	-0.0345
	(0.0163)	(0.0214)	(0.0296)
target_publ_last_5y	0.0190***	0.0139	0.00625
	(0.00661)	(0.00911)	(0.0135)
acquiror_publ_last_5y	-0.0118	-0.0292	-0.0413
	(0.0101)	(0.0204)	(0.0278)
acquiror_patent_last_5y	-0.0102	0.00281	-0.00899
	(0.00798)	(0.0136)	(0.0192)
target_patent_last_5y	0.00356	-0.00501	-0.0144
	(0.00744)	(0.0113)	(0.0142)
post_acq_publ_5y	0.00314	0.0121	0.0385
	(0.0137)	(0.0231)	(0.0310)
post_targ_publ_5y	-0.00822	-0.00761	-0.00565
	(0.00973)	(0.0123)	(0.0171)
post_acq_pat_5y	0.0122	-0.00478	-0.0129
	(0.0124)	(0.0180)	(0.0245)
post_targ_pat_5y	-0.00671	0.00887	0.0272
	(0.0108)	(0.0146)	(0.0188)
Constant	0.0186	0.0324*	0.0639**
	(0.0136)	(0.0175)	(0.0261)
Observations	875	875	875
R-squared	0.013	0.014	0.014

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Here in Table 7, Table 8, and Table 9 we report the results we obtain from a regression where the dependent variable is the cumulative abnormal returns over two, three and seven-day event windows around the acquisition announcement. In Table 7, we observe a positive effect of a dummy variable that assumes the value of 1 when the target has publications in the 5 years trailing the acquisition event. In Table 8, we report the results when we use 3-year measures for

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di DALAY HAKKI DOGAN
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the variables, while in Table 9 we report the results when we use count measures discounted with a decay factor of 0.15 for every year since the publication of a patent or the filing of a patent, also known as stock measures (e.g. Hall et al., 2005). Our main variable of interest, publications of the target, has a positive and significant effect on the cumulative abnormal returns. After accounting for the science activities of the acquiror, as well as the patenting activities of the acquiror and the target, the target's publication activities has a significant effect on the cumulative abnormal returns. This effect is apparent only in the 2 day window around the event, and disappears when we use alternative event windows of 3 days and 7 days.

Table 8

VARIABLES	(1) car_2day	(2) car_3day	(3) car_7day
post_shock	-0.0147	-0.0158	-0.0423*
	(0.0142)	(0.0179)	(0.0256)
target_publ_last_3y	0.0168**	0.0122	0.00371
	(0.00675)	(0.00936)	(0.0137)
acquiror_publ_last_3y	-0.00664	-0.0271	-0.0366
	(0.00901)	(0.0190)	(0.0257)
acquiror_patent_last_3y	-0.00760	0.00541	-0.00710
	(0.00798)	(0.0144)	(0.0197)
target_patent_last_3y	0.000199	-0.00990	-0.0169
	(0.00645)	(0.0103)	(0.0134)
post_acq_pat_3y	0.0246**	0.00388	0.0116
	(0.0122)	(0.0183)	(0.0246)
post_acq_publ_3y	-0.00732	0.00352	0.0222
	(0.0130)	(0.0220)	(0.0294)
post_targ_publ_3y	-0.00802	-0.00993	-0.00758
	(0.00984)	(0.0127)	(0.0173)
post_targ_pat_3y	0.000662	0.0210	0.0397**
	(0.0107)	(0.0146)	(0.0190)
Constant	0.0145	0.0296**	0.0584**
	(0.0119)	(0.0149)	(0.0228)
Observations	875	875	875
R-squared	0.014	0.016	0.014

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Tesi di dottorato "Essays on Corporate Science and Technological Change"
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Table 9

VARIABLES	(1) car_2day	(2) car_3day	(3) car_7day
post_shock	-0.00845	-0.0144*	-0.0211*
	(0.00615)	(0.00858)	(0.0120)
target_pub_stock	-9.15e-06	-1.99e-05	-3.05e-05
	(2.21e-05)	(2.14e-05)	(2.71e-05)
acquiror_pub_stock	-8.05e-06	-1.36e-05*	-2.15e-05**
	(6.46e-06)	(7.43e-06)	(1.08e-05)
acquiror_patent_stock	-1.16e-05*	-1.75e-05**	-3.20e-05**
	(6.58e-06)	(8.48e-06)	(1.24e-05)
target_patent_stock	-1.44e-05*	-4.62e-05***	-4.41e-05**
	(7.74e-06)	(1.09e-05)	(2.00e-05)
post_targ_publ_stock	8.53e-05*	9.88e-05*	0.000113*
	(4.90e-05)	(5.15e-05)	(6.49e-05)
post_acq_publ_stock	1.15e-05	1.07e-05	2.20e-05
	(9.40e-06)	(1.15e-05)	(1.51e-05)
post_targ_pat_stock	4.47e-06	3.37e-06	1.19e-05
	(2.68e-05)	(2.89e-05)	(4.05e-05)
post_acq_pat_stock	9.50e-09	7.75e-06	4.72e-06
	(9.29e-06)	(1.20e-05)	(1.74e-05)
Constant	0.0142***	0.0223***	0.0356***
	(0.00462)	(0.00706)	(0.0102)
Observations	875	875	875
R-squared	0.014	0.013	0.014

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 10

VARIABLES	(1) car_2day	(2) car_3day	(3) car_7day
post_shock	-0.00693	-0.0120*	-0.0176*
	(0.00570)	(0.00716)	(0.00962)
target_pub_stock	-9.23e-06	-1.99e-05	-3.07e-05
	(2.79e-05)	(3.50e-05)	(4.70e-05)
post_targ_publ_stock	8.42e-05**	9.18e-05**	0.000108*
	(3.72e-05)	(4.67e-05)	(6.27e-05)
Constant	0.0116**	0.0180***	0.0284***
	(0.00470)	(0.00590)	(0.00792)
Observations	875	875	875
R-squared	0.011	0.008	0.007

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

Tesi di dottorato "Essays on Corporate Science and Technological Change"
di DALAY HAKKI DOGAN
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In Table 10, we report the result of a regression where we regress the dependent variable of cumulative abnormal returns on an interaction between the dummy variable for years after the combinatorial chemistry shock (post), and the stock of publications of target firms. We find a statistically meaningful effect of the interaction on the cumulative abnormal returns. In table 11, we add the other main variables to the regression and still observe a statistically significant effect of the post-target publications interaction.

Table 11

VARIABLES	(1) car_2day	(2) car_3day	(3) car_7day
post_shock	-0.00691	-0.0120*	-0.0175*
	(0.00507)	(0.00702)	(0.00983)
target_pub_stock	-8.84e-06	-1.98e-05	-3.00e-05
	(2.21e-05)	(2.13e-05)	(2.69e-05)
acquiror_pub_stock	-4.00e-07	-6.36e-06	-6.75e-06
	(5.09e-06)	(6.33e-06)	(7.93e-06)
acquiror_patent_stock	-1.12e-05**	-1.17e-05*	-2.80e-05***
	(4.95e-06)	(6.39e-06)	(9.18e-06)
target_patent_stock	-8.55e-06	-4.15e-05*	-3.02e-05
	(2.22e-05)	(2.29e-05)	(2.97e-05)
post_targ_publ_stock	8.56e-05*	9.93e-05*	0.000114*
	(4.87e-05)	(5.10e-05)	(6.42e-05)
Constant	0.0131***	0.0206***	0.0331***
	(0.00403)	(0.00612)	(0.00887)
Observations	875	875	875
R-squared	0.013	0.012	0.013

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

All in all, we interpret these findings as supportive of hypothesis 1&2. Namely that the effect of targets' scientific capabilities become more valuable in the aftermath of a discontinuous technological change. In Table 12 below, we introduce the interaction between publication stock of the acquiror and the target in a regression where we keep the four main variables as independent variables. We observe a positive effect of the scientific publications of the target again. The interaction between the stock of publications of the acquiror and the target, has a

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di DALAY HAKKI DOGAN
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positive and significant effect on the dependent variable of cumulative abnormal returns when we use the cumulative abnormal returns variable with the seven-day event window. Hence, we do find evidence supporting hypothesis 2.

Table 12

VARIABLES	(1) car_2day	(2) car_3day	(3) car_7day
post_shock	-0.00841	-0.0138*	-0.0213*
	(0.00582)	(0.00813)	(0.0114)
post_acq_publ_stock	1.10e-05	1.36e-05	2.86e-05*
	(9.71e-06)	(1.26e-05)	(1.68e-05)
post_targ_publ_stock	9.26e-05	0.000103	0.000147*
	(5.94e-05)	(6.32e-05)	(7.67e-05)
target_pub_stock	-7.77e-06	-2.17e-05	-3.81e-05
	(2.43e-05)	(2.34e-05)	(2.98e-05)
acquiror_pub_stock	-1.25e-05	-2.20e-05**	-3.89e-05***
	(7.75e-06)	(1.04e-05)	(1.42e-05)
pub_stock_interact	-2.39e-08	1.23e-08	7.26e-08*
	(3.71e-08)	(3.61e-08)	(3.85e-08)
post_targpub_acqpub	-1.71e-08	-4.49e-08	-1.99e-07**
	(8.01e-08)	(8.59e-08)	(1.01e-07)
Constant	0.0133***	0.0209***	0.0335***
	(0.00434)	(0.00664)	(0.00963)
Observations	875	875	875
R-squared	0.013	0.011	0.012

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Discussion and Conclusion

Despite the importance of science in the industry, the empirical literature demonstrated a decline in the scientific efforts of U.S. firms (Arora, Belenzon, and Patacconi, 2018). The authors interpret their evidence as an indication that firms are carrying out the minimum amount of in-house research they need. Upon further exploration of alternative explanations of their findings, Arora and colleagues elaborate that their findings arise from a decrease in the benefits

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of carrying out internal research, rather than an increase in the costs of internal scientific research, or changes in publication processes. Here we argue that the role of science needs to be considered in conjunction with the technologies that the acquirors compete with. We advance the argument that when firms face discontinuous technological changes, the balancing act of internal scientific efforts breaks down.

As such, we expect to contribute to the literature on the interdependence of science and technology in two ways. First, we show that this relationship is subject to changes based on the technological regime that they operate in. While discussing their findings, Cassiman and Veugelers (2006) suggest that "…more importantly, our analysis reveals that the extent to which the innovation process relies on basic R&D affects the strength of the complementarity between innovation activities. Hence, complementarity is context specific." Our arguments support this notion of changing nature of complementarity between knowledge inputs. In particular, what seems like a substitution of internal scientific efforts with external scientific efforts in times of smooth sailing, may instead become a complementarity effect in times of turbulence. Our empirical results, while correlational in nature, looks at the market reaction to the acquisition events and factors in all the other information available on the market. In future work, we expect to show that the intertwined relationship between science and technology has different implications on firms acting in industries where knowledge is decomposable as opposed to industries where knowledge is more complex. In industries with complex knowledge, investments in science allow firms to develop a scientific capability. This scientific capability allows them to identify and assimilate new knowledge from the outside, use the science as a direct input in technologies and creates spillovers on the other activities of the firm.

Following a drastic change in the competences, companies have to adopt to the new regime through investments in science. In that regard, firms with scientific investments become more

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valuable in periods of technological changes. This adds to our understanding of the role of science in adopting to technological change and also hints at a down side of markets for technology. Companies sourcing scientific knowledge from the outside face a long-term challenge: When technological discontinuities hit an industry, companies that diminished their scientific capabilities face harder odds than their counterparts with lots of investments in science. We expect to observe similar effects in industries with technological discontinuities and where science plays an important role. Consistent with expectations, where science is already a valuable input into innovation, this effect is expected to be weaker, while industries where science is not useful for innovation, there should be virtually no difference.

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APPENDIX 1 FOR TABLE 1

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Variable	Variable Descriptions	N	Mean	Std. Dev.	Min	Max
car_2day	CAR with 2 day event window	875	0.0082734	0.0768779	-0.34179	0.63638
car_3day	CAR with 5 day event window	875	0.0110399	0.0964319	-0.42171	1.16473
car_7day	CAR with 7 day event window	875	0.0176371	0.1293424	-0.58271	1.48821
post_shock	1 if year>1994 & year<2001	875	0.6742857	0.4689091	0	1
pharma_dummy	1 if target is a pharma firm	875	0.488	0.5001419	0	1
target_publ_last_5y	1 if target has pubs in the 5 years before event	875	0.4251429	0.4946474	0	1
acquiror_publ_last_5y	1 if acquiror has pubs in the 5 years before event	875	0.7177143	0.4503691	0	1
acquiror_patent_last_5y	1 if acquiror has patents in the 5 years before event	875	0.7634286	0.42522	0	1
target_patent_last_5y	1 if target has patents in the 5 years before event	875	0.2308571	0.4216222	0	1
target_publ_last_3y	1 if target has pubs in the 3 years before event	875	0.3897143	0.4879643	0	1
acquiror_publ_last_3y	1 if acquiror has pubs in the 3 years before event	875	0.6845714	0.4649521	0	1
acquiror_patent_last_3y	1 if acquiror has patents in the 3 years before event	875	0.72	0.4492557	0	1
target_patent_last_3y	1 if target has patents in the 3 years before event	875	0.1954286	0.396757	0	1
acquiror_pub_stock	Stock of publications of the acquiror	875	134.0642	316.962	0	1777.031
acquiror_patent_stock	Stock of patents of the acquiror	875	132.4125	284.7145	0	1996.841
target_patent_stock	Stock of patents of the target	875	7.985615	71.74967	0	1086.406
target_pub_stock	Stock of publications of the target	875	34.1654	140.5898	0	1255.364
pub_stock_interact	Interaction between target and acquiror pub stocks	875	6360.008	54208.66	0	996712.8
post_targ_publ_stock	Interaction between target pubs stock and post	875	19.86588	106.1713	0	1210.579
post_acq_publ_5y	Interaction between acquiror pubs stock and post	875	0.4754286	0.4996815	0	1
post_targ_publ_5y	Interaction between target pubs in past 5y and post	875	0.2971429	0.4572613	0	1
post_acq_pat_5y	Interaction between acquiror pubs in 5y and post	875	0.5474286	0.4980301	0	1
post_targ_pat_5y	Interaction between target patents in 5y and post	875	0.1725714	0.3780925	0	1
post_acq_pat_3y	Interaction between acquiror patents in 3y and post	875	0.5108571	0.500168	0	1
post_acq_publ_3y	Interaction between acquiror pubs in 3y and post	875	0.4571429	0.4984448	0	1
post_targ_publ_3y	Interaction between target pubs in 3y and post	875	0.2697143	0.4440651	0	1
post_targ_pat_3y	Interaction between target patents in 3y and post	875	0.1451429	0.3524463	0	1
post_acq_publ_stock	Interaction between acquiror pubs stock and post	875	91.30054	269.8312	0	1777.031
post_targ_pat_stock	Interaction between target patents stock and post	875	6.474554	66.44885	0	1086.406
post_acq_pat_stock	Interaction between acquiror patents stock and post	875	89.47469	246.4864	0	1996.841
post_targpub_acqpub	Interaction of target and acquiror pubs stock and post	875	4814.337	48324.82	0	996712.8

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