Which governance of university-industry interactions increases the value of industrial inventions?

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Abstract

While evidence suggests that industry inventors' interactions with universities enhance invention value, the role of interaction governance has so far been overlooked. Relying on an original survey of industry inventors of European patents based in Italy, we show that governance matters. Personal contractual collaborations between firms and individual academics lead to higher-value inventions than collaborations mediated by university institutions. The former enable more effective exploitation of academic knowledge, by facilitating its full transmission and integration into the firm's knowledge base.

Key words: University-industry interactions, governance of collaborations, knowledge transfer, invention value, inventor survey, patent value.

JEL codes: O31; O32; O34.

1. Introduction

A large body of evidence, particularly since the 1990s, has shown that interactions with universities enhance industrial innovation in several ways, helping firms to develop products and processes that otherwise would not be developed or would be developed with substantial delays (Mansfield, 1991, 1998), and supporting better performance in terms of investment in R&D (Adams et al., 2003), higher levels of innovation (Zucker et al., 2002; Cassiman et al., 2012), and firm sales (Belderbos et al., 2004). Industry inventions that build on scientific knowledge tend to embody higher quality and relevance (Fleming and Sorenson, 2004; Cassiman et al., 2008), particularly when industry researchers have the opportunity to engage in direct interactions with academics (Gittelman and Kogut, 2003; Fabrizio, 2009; Arts and Veugelers, 2018; Czarnitzki et al., 2011; Dornbusch and Neuhäusler, 2015).

However, limited efforts have so far been made to understand the extent to which the value of industry inventions is influenced by the interactions' *governance*. Some studies explore the determinants of different types of governance (Cassiman et al., 2010; Bodas Freitas et al., 2013), but ignore the latter's effects on the value of the resulting inventions. Conversely, among studies investigating the determinants of the value of patented industrial inventions (see reviews in Reitzig, 2003, Sapsalis and van Pottelsberghe de la Potterie, 2003, and Gambardella et al., 2008), few explicitly consider the governance of the inventors' interactions with universities. Most explore the correlation between a patent's quality, proxied by the number of forward citations it receives (Lerner, 1994; Hall et al., 2007), and its reliance on scientific knowledge, proxied most often by its share of citations to the non-patent literature (Reitzig, 2003; Sapsalis et al., 2006; Fleming and Sorenson, 2004; Cassiman et al., 2008; Arts and Fleming, 2018), or the scientific affiliations of its co-inventors (Gittelman, 2005; Cassiman et al., 2012; Dornbusch and Neuhäusler, 2015). Other work links firms' innovative performance to collaborative activities with academics, such as firms' co-publications with 'star scientists' in basic research (Colen et al., 2014), firms' co-patenting with academic 'Pasteur' scientists that span the boundaries between academia and industry in applied research fields (Stokes, 1997; Baba et al., 2009), and firms' R&D alliances with universities (Subramanian et al., 2013).

The effect on invention value of the type of governance of university-industry interactions remains largely unexplored, despite evidence showing that the governance of interactions alters the incentives for parties to share knowledge (Heiman and Nickerson, 2004; Oxley and Sampson, 2004; Foss et al., 2010 Lakemond et al., 2016), and to translate it in ways that make it easier for the other party to absorb it and integrate it with its existing knowledge base (Badir et al., 2009; Foss et al., 2011; Schofield, 2013). In turn, greater knowledge absorption and integration increase firms' ability to produce more and better quality innovations (Cassiman et al., 2008; George et al., 2008; Fabrizio, 2009; Foss et al., 2011; Kotha et al., 2011).

The present study is based on original evidence from a survey of patent inventors working in industry - the PIEMINV survey (Cecchelli et al., 2012), and has several novel aspects. First, it proposes an original approach to the measurement of invention value which mitigates some of the traditional problems associated to inventor estimations: the ratio between the value of the invention that benefited the most from the contribution of academic knowledge, and the value of the most valuable invention in the inventor's portfolio. Instead of depending on precise value estimations, this variable only requires inventors to rank their own inventions based on their value. Second, the study evaluates the relative impact of two alternative types of governance of university-industry interactions (personal contracts stipulated with individual academic researchers and institutional contracts stipulated with the university) on the value of collaborative inventions produced by industry researchers. We employ various model specifications to control for selection bias and endogeneity, and individual and firm characteristics that might affect the value of an invention.

The empirical findings suggest that the type of interaction governance is relevant to the creation of economic value. Compared to institutional contracts, personal contracts give the firm greater control over the collaboration's objectives, and motivate academics to put more effort into translating their knowledge, so that it can be more effectively absorbed and integrated into the firm's knowledge base. Personal contracts also allow the firm to appropriate more of the knowledge resulting from the collaboration. High appropriability encourages industry inventors to share their tacit knowledge more freely with academic collaborators, which further facilitates knowledge integration. Since personal contracts allow greater integration of academic knowledge with the firm's knowledge, all else being equal they are conducive to the production of more valuable industrial inventions. This underscores the importance of promoting the integration of academic knowledge in the firm's knowledge base through both the development of absorptive capacity on the part of the firm, and contractual arrangements that encourage academics to invest effort in the translation of academic knowledge.

2. The governance of university-industry interactions and the value of industry inventions

2.1. The link between interaction governance and invention value

Evidence suggests that reliance on scientific knowledge enhances the quality of firms' inventions. Patents that contain references to scientific papers are more frequently cited (Fleming and Sorenson, 2004), and tend to generate forward citations in a broader range of technological fields (Cassiman et al., 2008). In particular, direct interactions between academic scientists and industry researchers, compared to access to disembodied knowledge, enhance invention value. It has been shown that the industry patents display higher quality if the industry researcher has close personal links to academia, previous experience of working in a public lab (Gittelman, 2005), experience of co-publication with academics (Gittelman and Kogut, 2003; Fabrizio, 2009; Arts and Veugelers, 2018), or has been part of a mixed team of academic and industry inventors (Czarnitzki et al., 2011; Dornbusch and Neuhäusler, 2015). It has also been shown that firms' collaborations with star scientists - particularly boundary spanning scientists who both patent and publish - increase patent quality and importance (Cockburn and Henderson, 1998; Zucker and Darby, 2001, Zucker et al., 2002; Baba et al., 2009; Subramanian et al., 2013; Colen et al., 2014). Sapsalis et al. (2006) found that self-citations to scientific papers on which the inventor collaborated directly increased the forward citation count.

Although direct interactions with academics increase the value of industry patents, little is known about the role played by the type of governance of these interactions. This might be due to difficulties in collecting relevant data. Although secondary data on inventors' affiliations and co-patents and co-publications are readily available, ad hoc surveys are needed to collect information on the governance of university-industry interactions.

It is reasonable to expect that different governance forms of university-industry interactions might affect the value of resulting inventions. Different governance forms, in fact, generate different incentives for academics and industry scientists to share knowledge, and for academics to translate their academic knowledge in order to facilitate its absorption and integration with the firm's existing knowledge base. In the following, we analyze in more detail the theoretical links between interaction governance on the one hand, and incentives to share and translate knowledge on the other.

(i) *Incentives to share tacit knowledge.* Tacit knowledge is necessary for the application of most codified pieces of knowledge (Kogut and Zander, 1996; Cowan et al., 2000; Foss et al., 2011) including basic scientific research (Mokyr, 1990; Dasgupta and David, 1994; Nelson and Rosenberg, 1994). This applies particularly to knowledge that is complex and systemic (Zander and Kogut, 1995), where blueprints and manuals only partially help, and the direct involvement of the knowledge creator is fundamental to ensure that knowledge is properly understood and exploited in order to generate commercializable innovations (Thursby et al., 2001; Agrawal, 2006; Santoro and Bierly, 2006). At the same time industry researchers' tacit knowledge is crucial for the integration of external knowledge in the firm's knowledge base (Bierly et al., 2009). Hence, all else being equal, governance forms that encourage academics and industry researchers to share relevant tacit knowledge and enable them to do this effectively, should lead to more valuable inventions.

(ii) *Incentives to translate knowledge to promote absorption and integration into the firm's knowledge base.* The firm's ability to absorb external knowledge and integrate it into its knowledge base has been studied extensively. The literature suggests that the firm's absorptive capacity depends to a large extent on its resources and competences (Cohen and Levinthal, 1990; Kogut and Zander, 1996; Hoang and Rothaermel, 2010; Bertrand and Mol, 2013). In the case of university-industry interactions, it has been shown that firms' engagement in R&D (Laursen and Salter, 2004), qualified human resources endowments (Gittelman and Kogut, 2003), and previous collaboration experience (Bruneel et al., 2010) can reduce the barriers to knowledge absorption (Muscio and Pozzali, 2013). However, the academic also plays a role in facilitating the firm's knowledge absorption: the more effort the academic invests in translating academic knowledge so that it can be integrated easily in the firm's knowledge base (Cowan et al., 2000), the more effectively this knowledge can be deployed to produce innovations (Schofield, 2013). The extent to which academics translate knowledge so that it can be used by external collaborators is, at least in part, dependent on the incentives they have for doing so (Agrawal, 2006). Hence, all else being equal, forms of governance of university-industry interactions that encourage academics to translate academic knowledge for easier integration in the firm's knowledge base, should lead to more valuable inventions.

Building on these two arguments, we suggest that it is the specific type of formal governance of the interaction and not just the presence of a direct interaction, that matters for the value of the invention being developed. In particular, governance of the interaction can be unilateral, as in the case of personal contracts between a firm and an individual academic, or shared by the parties, such as when the relationship between academics and industry personnel is mediated by the involvement of the university institution (Oxley, 1997; Geuna and Muscio, 2009; Bodas Freitas et al., 2013, 2014).

2.2. The effects of different forms of governance on invention value

Different forms of governance of the interaction between university and industry generate different incentives for sharing and translating knowledge, which affect both the firm's ability to absorb and integrate academic knowledge and the value of the resulting inventions. Different governance forms suggest different solutions to the agency problem of motivating individuals so that goals are aligned, and the coordination problem of organizing individuals so that their actions are aligned (Heath and Staudenmayer, 2000).

Personal contracts with individual academics

In the case of personal contracts, the firm contracts an individual academic expert to support one of the firm's projects. The firm organizes and directs the collaboration and is able to fully appropriate its results. Governance is unilateral, since the firm coordinates most aspects of the collaboration (setting the contractual terms, defining the content of the collaboration, managing the resulting intellectual property). Personal contracts with academics are particularly useful for small firms with limited resources (Bodas Freitas et al., 2013) since contracting directly with the academic entails lower costs than involving the university administration (Bodas Freitas et al., 2014). The alignment of the academic's actions to the firm's objectives is specified in the contract; hence, the academic has an incentive to align his or her actions to the firm's objectives to avoid premature termination of the project. Specifically, the academic is motivated to translate academic knowledge to allow its easy integration into the firm's knowledge base, which ensures that the firm's innovation objectives are achieved. These types of contracts can include a financial incentive to increase the academic's knowledge translation effort.

The unilateral setting of the collaboration's objectives (which encourages the academic's translation effort) and the unilateral appropriation of intellectual property by the firm (which reduces the risk of private knowledge leaking to external actors - Heiman and Nickerson, 2004 - and therefore encourages researchers to share their tacit knowledge) facilitate the integration of academic knowledge into the firm's knowledge base.

However, personal contracts do not solve the agency problem of aligning the academic's intrinsic goals to those of the firm. The academic may be unwilling to exert effort on a project that is aimed primarily at achieving the firm's objectives and distant from his or her academic interests, or which might be terminated if it shows signs of not yielding the desired results (Lacetera, 2009). The firm needs to monitor the academic's work to ensure investment of a sufficient level of effort (Gulati and Nickerson, 2008). Thus, this form of governance is preferred when the academic has an intrinsic reputational incentive to focus on the project, which reduces the firm's monitoring costs. There is empirical evidence showing that firms are more likely to stipulate personal contracts with academics who have graduated from the same institutions as the firm's personnel (Bodas Freitas et al., 2014), and therefore have a greater intrinsic incentive to commit effort to the collaboration than academics lacking relational proximity to the firm's personnel.

Contracts stipulated with the university institution

In the case of contracts stipulated between the firm and the university institution, governance is shared by the parties, since the contractual terms, content and objectives of the collaboration, and appropriation of its results are subject to negotiation. In particular, the project objectives are defined in a negotiated compromise between the university's and the firm's interests; these objectives have to satisfy the needs of both parties rather than just the firm's. Institutional governance is preferred by large firms and by R&D intensive firms with the internal resources required to manage R&D contracts (Bodas Freitas et al., 2013), since these negotiations increase the contracting costs. This governance form addresses the agency problem, since the academics involved work on the project as employees of the university, which should increase their incentives to invest effort in the project (Lacetera, 2009). Working on a project as part of their university employment provides reassurance that the collaboration will adhere to the norms and standards of the scientific community, and that the project will not be prematurely terminated if it does not lead to the desired results. Hence, this form of governance is more likely if the parties have no pre-existing social ties with one another: institutional governance has been shown to be preferred in situations where the parties are less likely to belong to the same social network such as if they are geographically distant (Bodas Freitas et al., 2013).

However, if it is unclear whether the firm will be able to appropriate all the results of the project, the firm will be less likely to share its tacit knowledge. Moreover, the incentives for academic knowledge translation might be lower than in the case of personal contractual collaborations, since achieving the project's objectives may not require the academic to tailor his or her knowledge to fit the firm's goals.

The differences between the two governance forms and their implications for knowledge sharing and translation are summarized in Table I.

Table I. Characteristics of personal and institutional contracts and their implications for knowledge sharing and translation

Aspects of collaboration governance	Personal contracts	Institutional contracts	Comparison: personal vs. institutional
Setting up and organization of the project	Firm hires a scientist as an external consultant to work on a firm project	Firm contracts with the university for a joint project	Lower contracting costs: preferred by less resourceful firms
Monitoring of effort	Firm organizes and monitors project activities, scientist works on the project as a self-employed external consultant	Firm and university jointly organize and monitor project activities, scientist works on the project as a university employee	Higher monitoring cost: preferred when parties share pre-existing social ties
Coordination of project activities	Firm decides objectives and activities of the project	Firm agrees on objectives and activities that are amenable to the university	Higher risk to the academic from not meeting firm's objectives → greater incentive for knowledge translation
Appropriation of project outcomes	Firm fully appropriates the results of the project	Firm negotiates with the university the results that will be diffused publicly, and those that the firm will appropriate	Lower risk for the firm of leakage of private knowledge → greater incentive for tacit knowledge sharing

Based on these arguments we can formulate our hypothesis about the impact of different types of collaboration governance on the value of the inventions produced by inventors who benefit from academic knowledge. The value of collaborative inventions increases with the absorption and integration of partners' knowledge, which is facilitated by greater tacit knowledge sharing and knowledge translation efforts. Therefore, we hypothesize that:

Collaboration with academics based on a personal contract between the inventor's firm and the individual academic results in more valuable inventions than if the collaboration contract is between the inventor's firm and the university institution.

In addition to the type of governance chosen, the integration of academic knowledge into industrial inventions is affected also by individual, firm, and industry specificities. Some individual characteristics of inventors increase their ability to absorb and integrate academic knowledge into the firm's knowledge base: we consider in particular the inventors' ability to engage with scientific theories rather than only with applied research outcomes, and their own direct experience of performing scientific research. The firm's engagement in R&D activities is known to enhance its absorptive capacity. Industry specificities also matter as the opportunities for successful exploitation of scientific research are distributed unequally across technological fields. In the following, we briefly discuss each of these factors' expected influence on invention value.

Inventors who rely primarily on theoretical scientific knowledge, when interacting with academics are more likely to produce more radical inventions, than inventors who rely primarily on applied knowledge (Carpenter et al., 1980; Della Malva et al., 2014). This is because scientific knowledge helps to guide the inventor through the technological landscape and to identify more useful combinations of previously unrelated knowledge domains (Gruber et al., 2013), and reduces the effort expended on fruitless search (Fleming and Sorenson, 2004). Firms benefit from scientific knowledge also in order to identify new paths to technological development and unlock obsolete technologies (Cassiman et al., 2012). In turn, inventors that produce more radical inventions are likely to generate more valuable patents (Nerkar and Shane, 2007). Radical inventions are likely to find application in a broad range of technological domains (Sapsalis and van Pottelsberghe de la Potterie, 2003), and hence can be exploited commercially in a variety of fields (Kotha et al., 2013; Reitzig, 2003). Moreover, radical inventions potentially face less competition in the final product market (Sapsalis and van Pottelsberghe de la Potterie, 2003). It can be argued also that inventors who rely on theoretical scientific knowledge are better able to identify and absorb relevant sources of academic knowledge than inventors who rely on applied knowledge (Gittelman and Kogut, 2003). This absorptive capacity allows them to better integrate academic knowledge in the firm's knowledge processes, which leads to more effective translation of research into new technologies (Fabrizio, 2009; Cassiman et al., 2008), and potentially to more valuable inventions.

Inventors' absorptive capacity is related to other individual features including active personal engagement in scientific research. Boundary spanning inventors with strong personal connections to scientific research through co-authorship with university scientists (Cockburn and Henderson, 1998), collaboration with university institutions (Cassiman et al., 2012), or previous employment in a university institution (Gittelman, 2005; Bjerregaard, 2010) can facilitate the transformation of academic knowledge into valuable inventions. The capacity to absorb university knowledge may also increase with education and more experience of interacting with cognitively distant collaborators as a result of higher career mobility.

The firm's general context influences inventors' ability to exploit academic knowledge. In particular, the firm's engagement in R&D activities (especially when aimed at technological recombination; Soh and Subramanian, 2014) is an important predictor of the ability to exploit academic knowledge (Laursen and Salter, 2004). It is important to control also for technological specificities. The opportunities for successful exploitation of scientific research are concentrated in certain technological fields such as biotechnology and pharmaceuticals, information and communication technology, and nanotechnology (Callaert et al., 2006). Firms that innovate in these fields are more likely to benefit from academic research to produce valuable inventions (Mansfield, 1991; Cohen et al., 2002; Laursen and Salter, 2004; Abreu et al., 2008).

3. Research design

3.1. Industry inventors in Piedmont: the PIEMINV survey

Piedmont is one of the most technologically advanced regions in Italy with much higher investment in R&D compared to the rest of Italy (Bodas Freitas et al., 2013), and scientific and technological performance in line with the EU average (European Commission, 2014). The region has an important manufacturing base with a relevant presence in R&D-intensive industries such as automotive, aeronautics and aerospace, and telecommunications, and in traditional industries such as food and fashion. It hosts three important universities, two of which are in Torino, the region's largest city. The University of Torino is one of the oldest Italian universities, and is a large (ca. 63,000 students) multidisciplinary institution. The Politecnico of Torino has almost 29,000 students and is one of the three elite technical universities in Italy. The more recently (1998) established University of Piemonte Orientale is a smaller university (almost 10,000 students) with campuses in three small towns in the region. These characteristics make Piedmont a relevant case to explore how the governance of university-industry interactions contributes to the value of industrial inventions.

The PIEMINV survey was targeted at the population of inventors named on at least one European Patent Office (EPO) patent application between 1998 and 2005, resident in Piedmont, and resulted in 938 valid responses (31% response rate).[1] The questionnaire was designed to investigate various aspects of university-industry interactions, and to enable quantitative measurement of the universities' contribution to the invention process. The questionnaire included four sections; in this paper we focus on the information derived from the responses to section four, which focused on assessment of the economic impact of university knowledge. It asked for details of two specific inventions: the one that had benefited most from academic knowledge, and the inventor's most valuable invention. We limited our questions related to

[1] See Appendix A for a short methodological description of the survey. For a detailed analysis of the PIEMINV survey see Cecchelli et al. (2012).

value information to two inventions in order to maximize the response rate (see section 3.2 for a detailed explanation of our invention value measure). To our knowledge, PIEMINV is the first survey to collect such information, and to distinguish among two different contractual governance forms in relation to the value of the inventions.

Twenty-three inventors were removed from the database because they were employed by a public institution (university, public research organization, government agency) at the time of patent filing, leaving a total of 915 industry inventors. Additional information on inventor's employer (number of employees, revenue, head office location, number of branches, year of foundation, sector, legal status, industry) was collected from the CERVED database of Italian companies' accounts, and other public online sources. Of the 363 firms in the sample, this information was available for 298 (corresponding to 738 inventors); for non-public small and micro firms some information was missing. We collected the number of patents filed by the inventor's firm from 1998 to 2005, from the Derwent Innovations Index. For each inventor we collected the number of patent applications and the number of patents granted between 1998 and 2005, the most common type of assignee, the average number of backward citations, the average number of forward citations, the average number of citations to academic papers, the date of first patent application, and the most frequent technology class.[2]

The mean age of the sample is 48.1 years, with most in the 41-50 cohort (36.7%). The mean age is lower for women (41.6 years) who constitute 8.2% of the sample.[3] Younger inventors are more highly educated on average: 76.8% of under-40s have a tertiary degree (sample average 59%), and 5.6% have a PhD (sample average 3.8%). Inventors are characterized by low levels of education and career mobility: 79.5% completed their primary and secondary education locally, and 31.5% had worked for only one organization; 60.7% had worked for less than five

[2] Classification by macro-technology classes is according to OST-DT7 (OST, 2004).

[3] The share of women in the PIEMINV survey is higher than the Italian (2.7%) and the European (2.8%) shares, reported by the PatVal survey (Giuri et al., 2007).

different organizations, and only 7.8% had had more than five different employers. Mobility is correlated to education attainment: more highly educated inventors are more mobile.

Most (60.8%) inventors work in large firms (more than 250 employees), in five manufacturing sectors: fabricated metal products (except machinery and equipment); computers, electronic and optical products; electrical equipment; machinery and equipment n.e.c.; motor vehicles, trailers and semi-trailers.

Almost two-thirds of inventors have patented less than five inventions; the average is 1-2 patented inventions each. Only 8% have more than 16 patented inventions. The average number of non-patented inventions is almost double the number of patented inventions (ca. 3-5 non-patented inventions), in line with evidence for other regions and countries (Acs and Audretsch, 1988; Arundel and Kabla, 1998).

After a first cleaning of the original dataset for missing observations, incomplete answers, and missing information on inventor's employing firm, we were left with a sample of 657 observations including inventors who collaborated with a university and benefited from academic knowledge, and inventors who did not declare any substantial contribution from academic knowledge.[4]

3.2. Constructing a measure of invention value

As discussed previously, the literature investigating the impact of academic knowledge on patent value tends to measure it using forward citations counts. Forward citations are easy to retrieve from patent databases but suffer from several limitations (van Zeebroeck, 2011; Squicciarini et al., 2013) including differences in citation standards across classes. Also, the

[4] The 657 inventors that accounted for complete questionnaires and are used for the empirical analysis, are not significantly different from the overall sample of 915 respondents. Mean age is 48.5 years, and the share of women is 7.3%; 58% of inventors have a tertiary degree or a PhD and 8.7% have experience of working at a university. On average, each inventor was involved in 2.2 EPO applications between 1998 and 2005.

number of forward citations can indicate a "crowded" research field rather than patent quality (Czarnitzki et al., 2011). Other proxies for the economic value of patents include patent opposition and renewal data (where patent value is captured by the extent to which companies are willing to spend resources on litigation or patent renewal; Priest and Klein, 1984; Pakes and Simpson, 1989; Bebchuk, 1994; Lanjouw and Schankerman, 2004; Arts and Fleming, 2018), patent claims, the extent of the protection sought in a patent application (Lanjouw and Schankerman, 2004; Beaudry and Kananian, 2013), company start-up activity (capturing whether the patent led to the creation of a high-tech start-up; Shane, 2001), probability of a patent being granted (Guellec and van Pottelsberghe de la Potterie, 2000), and composite indicators (Lanjouw and Schankerman, 2004; van Zeebroeck, 2011).

None of these variables measures economic value directly, and all are poorly correlated, suggesting that they capture different aspects of patent importance or patent quality.[5] A few survey-based studies asked respondents to provide estimates of the monetary value of their patents (Harhoff et al., 1999; Scherer and Harhoff, 2000; Reitzig, 2003; Gambardella et al., 2008). This approach has shortcomings related mainly to data accuracy and reliability, since estimating the commercial value of a patent is difficult, especially for the large share of patents that are not traded but are used internally or strategically (e.g. blocking patents). The survey design might have to accept a trade-off in the link between patent value and features of the invention process. Inventors may not have details about patent value since this information often is reserved to product/R&D managers and executives (Mansfield, 1991). However, they are better able to answer questions about the invention process.

We propose a new measure of patent value that accounts for some of the limitations of survey-based approaches. Section IV (assessment of the economic impact of university knowledge) of

[5] In a recent study analyzing how well several proxies for the economic value of patents perform in predicting actual economic value, Capponi et al. (2017) find that the number of claims appears poorly correlated with economic value, while forward citations, and especially family size and number of renewals, perform better (a result consistent with Harhoff et al., 1999), although still not well; the best results are obtained using a composite indicator similar to that proposed by Lanjouw and Schankerman (2004).

the PIEMINV survey asked inventors to identify and provide information on two specific (patented or not) inventions: the invention that benefited the most from university knowledge,[6] and the invention that had the highest economic impact. For each invention, respondents were asked to provide information on its monetary value (€'000 at current prices).[7] Among the sample of inventors with two or more patented inventions, 164 (24.9%) stated that at least some of their inventions had benefited from university knowledge, and provided information on two inventions.

Since the inventor might find it difficult to estimate the exact value of an invention, with some overestimating it and others underestimating it, we do not use absolute economic value but construct two relative measures. First, we count how many inventors stated that the invention that had benefited most from academic knowledge was also the invention that had had the highest economic impact. *Highest_economic_impact* is a dummy variable that is equal to 1 if the inventions coincide: 53 out of 164 respondents (32.3%) stated that the invention that had received the greatest contribution from academic knowledge was also their most valuable invention, suggesting an important role of academic knowledge in the process of value creation.

We also calculated the ratio between the value of the invention with the highest contribution from academic knowledge, and the value of the invention with the highest economic impact. This variable, *Relative_economic_value,* takes values between zero and 1. Using a relative measure of invention value overcomes the problem of lack of comparability across inventors, since it requires only the assumption that each inventor's evaluations are consistent. This ratio also eliminates unit of measurement problems (common to this type of question), and regardless of the subjective and heterogeneous measures used by inventors, provides an indication of the value of the invention that benefited most from academic knowledge with respect to the most

[6] About 85% of inventions that had benefited greatly from academic knowledge had been patented.

[7] The question was based on Gambardella et al. (2008) and was worded as follows: "Suppose that, on the day that the invention was completed (or, if the invention was patented, on the day that the patent was granted) a potential competitor had expressed an interested in purchasing it, what is the minimum price that the invention's owner would have asked for it?"

valuable invention in the inventor's portfolio. The value of the invention with the highest economic impact also allows us to net out from our estimates the intrinsic quality of inventors which clearly is correlated to the value of their invention.

The variables *Highest_economic_impact* and *Relative_economic_value* are our main dependent variables. Table II shows that *Relative_economic_value* has fewer observations than the binary variable *Highest_economic_impact*, since not all the inventors who identified the two inventions were able or willing to provide specific monetary values.[8] Figure 1 plots the distribution of the (logs of) the values of the invention with the highest academic contribution. As expected, the distribution is extremely skewed and displays a large range of values, in line with the findings in the patent value literature.[9]

Focusing only on the inventions with the highest contribution from academic knowledge, and assessing their value compared to the most valuable inventions has some limitations. It reduces the validity of our measures capturing the most important impact and may not be representative of the whole spectrum of the contribution of academic knowledge to all the inventive activities of firm inventors. However, the literature suggests that the value of patents is highly skewed, with a very small number of patents related to important innovations with high economic value,

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[8] Among the 164 inventors who provided information on two inventions, 77 did not provide an economic value for one or both inventions. In those cases we cannot calculate the *Relative_economic_value* variable. Among these 77 individuals, 54 had *Highest_economic_impact* =0 and 23 had *Highest_economic_impact* =1. This means that in this restricted subsample of excluded inventors the share of *Highest_economic_impact* =1 is 30%, which is in line with the overall average of 32% (53 inventors over 164, see Figure 1). Therefore, we believe that the inventors for whom we cannot compute *Relative_economic_value* represent a fairly random subsample of respondents.

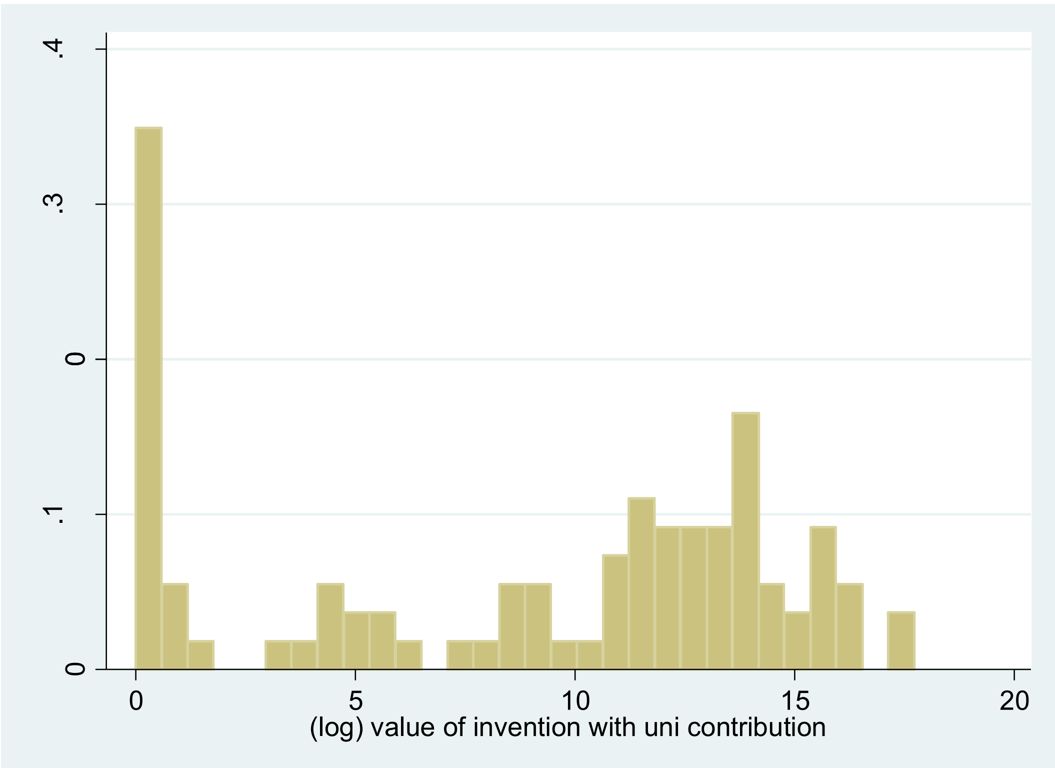
[9] We modeled invention value using the number of forward citations to the patented invention. However, not all inventors provided the specific identifier for their invention, which reduced the number of observations for the empirical analysis. Pairwise correlation shows that our measures of invention value are weakly correlated to the patent based measures, making the impact of governance type less clear cut when forward citations is the dependent variable. This is due, first, to the fact that studies that use forward citations especially in the context of university-industry collaboration, often focus on science-based disciplines, while our inventors work in the fields of mechanical engineering (30% of the 164 inventors) and electronics (29%). This means that forward citations in our case, are less strictly linked to economic value. Second, we interpret these findings as confirmation that forward citations are good proxies for the invention's technological relevance, but may not be correlated to the invention's economic value to the firm that introduced it. Thus, we suggest that the form of governance will affect the firm's ability to benefit from the invention, but do not hypothesize about the impact of governance type on its contribution to later inventions (possibly by other firms).

and a large number of patents that are never exploited. Therefore, our measures should identify innovations with significant economic impact.

Table II. Distributions of variables capturing invention value

	Highest_ economic _impact	*Relative_ economic _value*	Economic value of inventions with highest contribution from university knowledge	Economic value of inventions with highest economic impact
Observations	164	87	87	87
Mean	0.304	0.53	2,158,749	6,044,990
St. deviation	0.461	0.43	7,741,929	24,700,000
Minimum	0	0	0	0
Maximum	1	1	50,000,000	200,000,000
Skewness	0.85	-0.05	5.55	6.51
Kurtosis	1.71	1.26	34.35	48.3

Figure 1. Distribution of the value of the invention with highest university contribution



3.3. Methodology

We want to explain the factors correlated to the value of those inventions with an important contribution from academic knowledge relative to the most valuable invention in the inventor's portfolio. We are interested in the governance of the university-industry interaction, and control for inventor characteristics and several firm and industry specificities. We propose the following linear model:

$$y_i = \alpha + \sum_j \beta_j GOV_{ij} + \sum_l \delta_l INV_{il} + \sum_m \gamma_m FIRM_{im} + \sum_n \varphi_n TECH_{im} + v_i \qquad (1)$$

where y_i is a proxy for the value of inventor *i*'s invention which benefited most from the contribution of academic knowledge, relative to the inventor's most valuable invention; *GOV* is a set of variables capturing the governance of the interactions between university and industry; *INV* is a set of variables capturing some inventor characteristics; *FIRM* and *TECH* are sets of firm and technological control variables; and v_i is an idiosyncratic error term.

In estimating equation (1) we are aware of the risk of selection bias. Only those inventors who said they had benefited from academic knowledge were able to assess its contribution to the value of their inventions. Hence, we need first to control for whether this subset of inventors is significantly different from the rest of the sample. Also, some of the factors influencing the value of the academic knowledge contribution are likely to influence the probability of having benefited from it. To avoid underestimation of these variables, we estimate a selection equation that indicates whether inventors were able to benefit from academic knowledge, and an intensity equation to measure the effect of different variables on the relative economic value of those inventions that benefited from academic knowledge.

Our preferred selection variable (*Contribution*) is a dummy that is equal to 1 if at least some of the inventor's inventions benefited greatly from academic knowledge.[10] However, to check the

[10] This variable is based on inventors' answers to the following question: "How many of your inventions benefited from an important contribution from academic knowledge? By "contribution" we mean any resource, idea, clarification, assessment provided (formally or informally) by a university, which was

robustness of our findings we use the alternative selection variable *Cooperation* which is equal to 1 if the inventor had experience of cooperation with a university institution or an individual university scientist.[11] This variable is used in several studies to analyze university-industry relationships. We prefer the selection variable *Contribution* because we believe it is a better measure of the inventors' individual ability to benefit from academic knowledge. In the selection equation we are interested in understanding the factors that allow inventors successfully to exploit academic knowledge, while cooperating or not with a university is influenced mainly by the characteristics of the firm employing the inventor (e.g. large firms cooperate more). In the empirical analysis we use two specifications of the model: when the dependent variable *y* is the binary variable *Highest_economic_impact*, we estimate a probit model with sample selection, when the dependent variable is the continuous variable *Relative_economic_value* we estimate a Tobit type II model (Amemiya, 1984).

Personal contractual collaborations: instrumental variables strategy

A problem in estimating equation (1) is that the (unobserved and idiosyncratic) quality of an invention might be correlated to both invention value and the specific form of governance of the university-industry interactions. That is, in the case of projects that can potentially generate higher (unobserved) quality inventions, and therefore, higher expected economic value, firms might prefer personal contracts, since the property rights to those inventions would be assigned directly to the firm (Bodas Freitas et al., 2014). This results in a typical problem of reverse causality, which would bias estimates of the treatment (personal contracts) on the value of the invention. To overcome this, we employ an instrumental variables (IV) strategy, using as instruments three variables which are likely to be correlated to the choice to govern the

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instrumental in realizing the invention". The possible answers were: None, less than half, more than half, All. *Contribution* is equal to 1 if at least "less than a half" was selected by the respondents.

[11] The specific question in the PIEMINV survey is: "Have you any experience of collaboration with a university or contracts with individual university employees? (Yes / No)"

interaction by a personal contract but which are not correlated to the specific value of the invention considered.

We know that the choice of personal contracts is influenced by various factors (Bodas Freitas et al., 2014); however, our exclusion restriction relies on the fact that these factors are unlikely to affect the value of the invention. In particular, relational proximity between the industry inventor and the academic facilitates the choice of a personal contract as the preferred means to access university knowledge.

We use a set of instruments to capture this relational proximity. The first is the variable, *Local,* which is equal to 1 if the inventor's highest education attainment is secondary school level, in the region. Among inventors without university education, having been educated to secondary level in the region in which they are working, increases their likelihood of belonging to the same social networks as academics working in the that region who, given the low level of mobility in the region, are likely also to have been educated there.

Collaborating with the university from which the inventor graduated (alumni interactions) also increases the probability of using personal contracts (Bodas Freitas et al., 2014). Again, it is likely that the inventors will have greater relational proximity to university researchers in their alma mater. We built a variable, *Alumni_polito,* which is equal to 1 if the inventor graduated from the Politecnico di Torino and declares frequent professional interactions with the institution. The model estimation includes a series of robustness checks to confirm the endogeneity of these instruments.

The PIEMINV survey asked inventors with which universities they had personal contractual collaborations. The geographic pattern of these collaborations shows that there is frequent collaboration with scientists in Italian universities outside of Piedmont. We believe this is determined by the alumni connections of inventors who graduated from universities outside Piedmont, or the existence of professional networks built over the course of the inventor's career which allow privileged personal interactions with individual academics in other Italian regions. Data on inventors' scientific publications (extracted from Scopus) were used to build a third IV, *Share Italy*, which measures the share of Italian co-authors from outside of Piedmont in the inventor's total number of co-authors. The share of Italian co-authors not resident in Piedmont proxies for the importance of the inventors' social networks outside of Piedmont which are also likely to lead to personal collaborations.

We adopt an over-identified IV strategy with three instruments for one endogenous variable. Following Angrist (2001), we adopt a linear probability model in order to focus explicitly on identifying the causal effect of treatment on the treated: we use two stage least squares (2SLS) to estimate equation (1).

3.4. Descriptive statistics

3.4.1. The selection equation

In the selection equation we use a set of independent variables that are identified in the literature as likely to influence the probability that an inventor collaborated with an academic in the development of his or her invention. Table III indicates how we construct each variable, and table IV reports the descriptive statistics for the variables used in the first stage selection equation for 657 observations.

Inventor characteristics

We control for the personal characteristics of inventors that might facilitate collaboration with an academic. More highly educated inventors (*HEducation* captures whether the inventor has a bachelors, masters, or doctoral degree) and inventors with experience of working in a university (*University Work Experience*) might be more inclined to consult a source of university knowledge, and might be better able to understand the scientific literature and communicate with academics. More productive inventors (*Technological Productivity,* defined as the number of patent applications to the EPO in the period 1998-2005) may be more experienced and also more likely to benefit from university knowledge. Finally, we control for *Age* (and *Age* squared) and gender.

Firm characteristics

Several firm characteristics might affect the probability of interacting with a university. The literature shows that larger and R&D-intensive firms are more likely to interact with universities. Therefore, we consider a set of firm size dummies: micro-firms (less than 10 employees) and individual inventors; small and medium sized firms (10-250 employees); large firms (more than 250 employees). Table IV shows that the majority (68%) of inventors work in large firms, with the remaining 32% distributed fairly evenly between micro and small and medium sized firms. We control also for each firm's R&D activity; *Technological capability* measures the number of EPO patents granted in the period 1998 to 2005 at the firm level. The average number of patents per firm is 262, with large firms accounting for around 2,000 patents and some firms registering zero patents in the time window. We include a dummy for whether the firm's ownership is not Italian (*Foreign firms)*; some 10% of firms are foreign-owned.[12]

Finally, we include several dummies to capture the most common technology class in the inventor's portfolio among electrical engineering and electronics, process engineering, instruments, chemicals, pharmaceutical, mechanical engineering, and consumer goods. Compared to economic activity codes, these variables more precisely capture the inventor's technology specialism, and especially in the case of large multiproduct firms where industry affiliation might be too generic.[13] Table IV shows that electrical engineering and mechanical

[12] These are either Italian subsidiaries of foreign firms, or are headquartered just across Italian border, e.g. some Swiss firms are located close to the Italian border. Since the PIEMINV survey targeted inventors resident in the Piedmont region, the sample does not include inventors working for foreign firms located at a distance from the Italian border.

[13] Two inventors working, for example, in the same large automotive firm might be specialized in different technological fields (e.g. electronics and mechanical engineering). Use of a sectoral dummy would be misleading since different technological fields are likely to have different needs for academic knowledge.

engineering are the most common technology classes indicated by inventors. This is consistent with the regional industry specialization, and distinguishes the present study from most previous work that focuses on the biomedical and pharmaceutical industries.

Table III. Description of variables.

Variable	Description
Selection equation	*Dependent variables*
Contribution	Dummy variable equal to 1 if at least some of the inventor's inventions received important contributions from academic knowledge
Cooperation	Dummy variable equal to 1 if the inventor has had experience of cooperation with a university institution or an individual university scientist
Main equation	*Dependent variables*
Highest economic impact	Dummy variable equal to 1 if the inventors stated that their invention that had benefited most from academic knowledge coincided with the invention that had the highest economic impact.
Relative economic value	Ratio between the value of the invention with the highest contribution from academic knowledge, and the value of the invention with the highest economic impact.
	Independent variables
Collaboration	Dummy variable equal to 1 if the development of the invention with the highest academic knowledge contribution involved any form of contract-based collaboration with university scientists
Pcontracts	Dummy variable equal to 1 if the development of the invention with the highest academic knowledge contribution involved a personal contract signed directly by the academic researcher involved.
Institutional	Dummy variable equal to 1 if the development of the invention with the highest academic knowledge contribution involved a contract signed by the university administration
Theories	Dummy variable equal to 1 if the inventor indicated "scientific theorems and principles" as the most useful type of academic knowledge for the development of his/her inventions.
Methods	Dummy variable equal to 1 if the inventor indicated "methodologies, techniques, and instruments" as the most useful type of academic knowledge for the development of his/her inventions.
Applied	Dummy variable equal to 1 if the inventor indicated "solutions to technological problems/support for prototyping" as the most useful type of academic knowledge for the development of his/her inventions.
Contact	Dummy variable equal to 1 if the inventor indicated "information about other relevant sources of knowledge/about other organisations" as the most useful type of academic knowledge for the development of his/her inventions.
	Individual Characteristics
Male	Dummy variable equal to 1 if the inventor is a man
Age	Age of the inventor in 2009
HEducation	Dummy variable equal to 1 if the inventor has a bachelors, masters, or doctoral degree
University work experience	Dummy variable equal to 1 if the inventor has experience of working in a university
Publications	total number of the inventor's scientific publications in the Scopus database.
Academic co-publications	Total number of the inventor's publications in the Scopus database which involved a co-authorship with an author with an academic affiliation.
Technological productivity	number of the inventor's patent applications to the EPO in the period 1998-2005
Firm Characteristics	
Micro firms	Dummy variable equal to 1 if the inventor works in a firm with less than 10 employees
Small and Medium Firms	Dummy variable equal to 1 if the inventor works in a firm with between 10 and 250 employees
Large Firms	Dummy variable equal to 1 if the inventor works in a firm with more than 250 employees
Foreign Firms	Dummy variable equal to 1 if ownership of the inventor's firm is not Italian
Technological capability	Number of EPO patents (in 000s) granted in the period 1998 to 2005 at the firm in which the inventor is employed
Instruments	
Local	Dummy variable equal to 1 if the inventor's highest educational attainment is a secondary degree earned in the Piedmont region.
Alumni_polito	Dummy variable equal to 1 if the inventor graduated from the Politecnico di Torino, and claims to have frequent professional interactions with that institution.
Share Italy	Share of Italian co-authors outside of Piedmont in the inventor's total number of co-authors.

Table IV. Descriptive statistics. All inventors

Variable	Obs	Mean	Std. Dev.	Min	Max
Governance					
Contribution	657	0.250	0.433	0	1
Cooperation	657	0.452	0.498	0	1
Individual Characteristics					
Male	657	0.927	0.260	0	1
Age	657	48.521	9.940	30	88
HEducation	657	0.583	0.493	0	1
University work experience	657	0.087	0.282	0	1
Technological productivity	657	2.213	2.498	0	24
Firm Characteristics					
Micro firms	657	0.102	0.303	0	1
Small and Medium Firms	657	0.215	0.411	0	1
Large Firms	657	0.683	0.466	0	1
Foreign Firms	657	0.107	0.309	0	1
Technological capability	657	262.938	511.852	0	4808
Technological dummies					
Electrical engineering	657	0.251	0.434	0	1
Instruments	657	0.100	0.301	0	1
Chemicals	657	0.065	0.248	0	1
Pharmaceuticals	657	0.014	0.116	0	1
Process Engineering	657	0.131	0.338	0	1
Mechanical Engineering	657	0.368	0.483	0	1
Consumer goods	657	0.070	0.255	0	1

3.4.2. The main equation

The following independent variables are used in the main equation (table V reports the descriptive statistics relating to the variables used in the main equation for 164 observations, which are a subset of the 657 observations used in the selection equation).

Governance

Collaboration indicates whether the development of the invention with the highest academic knowledge contribution involved any form of contract-based collaboration with a university scientist. To test our hypothesis, we contrast two types of governance of collaborations: personal contracts signed directly by the academic (*PContract*) or contracts stipulated with the university institution (*Institutional*). Table V shows that 23.2% of the inventions with the highest contribution from academic knowledge involved personal contracts with individual scientists, and 28.7% involved contracts with the institution. The pairwise correlation in Appendix table B1 shows that the two types of governance are negatively correlated, suggesting that inventors do not use them simultaneously. Table A1 in Appendix A shows the specific question of the questionnaire used to build our governance measures. Since we were mainly interested in contrasting these two types of formal governance, the question did not explore the full spectrum of interactions (different from research contracts) that inventors might have had with academics in the course of the development of the invention.[14] Hence, the inventors might have engaged also in specific kinds of non-contractual interactions in parallel with, or in place of, contractual interactions during the development of the invention.

Inventor characteristics

We control for several inventor characteristics. To capture inventor's reliance on different types of academic knowledge, we include four dummy variables for scientific theorems and principles (*Theories*), methodologies, techniques, and instruments (*Methods*), solutions to technological problems/support for prototyping (*Applied*), and information on other relevant sources of knowledge/ other organizations (*Contact*). Our 164 respondents exploit academic knowledge mainly to obtain information about other relevant sources of knowledge (59.8%), and to find solutions to technological problems (61.0%); theoretical knowledge was declared important by 54.9%, and methodologies, techniques, and instruments by 50.6%. To capture an inventor's personal engagement in science, we use their total number of scientific publications in the Scopus database (*Publications*). We control also for inventor's age (and age squared) and gender. Finally, we use the same firm and technology controls as in the selection equation.

[14] Among the non-research contract types of interactions we included the supervision of master or PhD students, as well as the sharing of facilities, such as labs or equipment.

Table V. Descriptive statistics, restricted sample

Variable	Obs	Mean	Std. Dev.	Min	Max
Governance					
Collaboration	164	0.488	0.501	0	1
Pcontracts	164	0.232	0.423	0	1
Institutional	164	0.287	0.454	0	1
Types of university knowledge					
Theories	164	0.549	0.499	0	1
Methods	164	0.506	0.501	0	1
Applied	164	0.610	0.489	0	1
Contact	164	0.598	0.492	0	1
Individual Characteristics					
Male	164	0.909	0.289	0	1
Age	164	48.5	10.573	31	88
HEducation	164	0.793	0.407	0	1
University work experience	164	0.183	0.388	0	1
Publications	164	5.859	15.168	0	144
Academic co-publications	164	2.500	6.530	0	46
Technological productivity	164	2.665	3.203	0	24
Firms Characteristics					
Micro firms	164	0.085	0.280	0	1
Small and Medium Firms	164	0.165	0.372	0	1
Large Firms	164	0.750	0.434	0	1
Technological capability	164	296	565.504	0	2869
Technological dummies					
Electrical engineering	164	0.287	0.454	0	1
Instruments	164	0.146	0.355	0	1
Chemicals	164	0.104	0.306	0	1
Pharmaceuticals	164	0.024	0.155	0	1
Process Engineering	164	0.091	0.289	0	1
Mechanical Engineering	164	0.311	0.464	0	1
Consumer Goods	164	0.037	0.188	0	1
Instruments					
Local	164	0.030	0.172	0	1
Alumni_polito	164	0.103	0.305	0	1
Share Italy	164	0.180	0.296	0	1

4. Results

Table VI presents the results of the selection models using the two selection variables already described, to examine the characteristics of inventors able to benefit from academic knowledge or to collaborate actively with an academic institution.

Column (1) presents the results of a probit regression with the dependent variable *Contribution*:[15] it shows a positive and significant effect of higher education (*HEducation*), of having spent at least one month working at a university (*University Work Experience*), and of the number of patent applications to the EPO in the period 1998-2005 (*Technological Productivity*). Firm size dummies are not significant, suggesting that there are no substantial differences among small and large firms in relation to the ability of their inventors to obtain important contributions from academic knowledge. Also, the firm level variable *Technological capability* is not significant, indicating that inventor's individual characteristics are a better predictor than firm characteristics of the capability to develop a contribution based on academic knowledge. Although not reported in the table, some of the technology class dummies are significant, confirming the existence of relevant differences across technologies.

In table VI column (2) the dependent variable is the probability of having collaborated with a university (*Cooperation*). The results are similar to those from the previous estimation, although the coefficients of firm size are different. In line with the literature on university-industry interaction, if the probability to cooperate is the dependent variable, large firms have a positive and significant coefficient.

Given the similarity of the results across specifications we prefer to use *Contribution* as our selection variable, since we believe it more precisely captures the ability of inventors to benefit from academic knowledge.[16]

[15] We also modeled *Contribution* as an ordinal variable following the formulation of the survey question. In this estimation, the coefficients of age and age squared are significant, suggesting the existence of a U-shaped relationship between age and the ability to benefit from university knowledge.

[16] We ran our empirical analyses using *Cooperation* as a selection variable; this did not affect our results.

Table VI. Selection equations

VARIABLES	(1) *Contribution*	(2) *Cooperation*
Inventor chracterisitcs		
HEducation	0.183***	0.305***
	(0.035)	(0.042)
University Work Experience	0.231***	0.247***
	(0.073)	(0.077)
Age	-0.022	0.035*
	(0.015)	(0.019)
Age^2	0.000*	-0.000*
	(0.000)	(0.000)
Technological Productivity	0.013*	0.030***
	(0.007)	(0.009)
Male	0.045	-0.081
	(0.056)	(0.080)
Firm characteristics		
Small and Medium Firms	-0.077	0.156*
	(0.059)	(0.091)
Large Firms	0.009	0.246***
	(0.060)	(0.076)
Foreign	-0.026	-0.013
	(0.054)	(0.071)
Technological capability	-0.024	0.036
	(0.035)	(0.047)
Technological dummies	***yes***	***yes***
Observations	657	657
pseudo-Rsquared	0.105	0.165
Log-likelihood	-330.3	-377.6

Reported coefficients are marginal effects (at the sample means) from a probit. The reference category for the size dummies are micro-companies and individual inventors. Standard errors robust to heteroskedasticity. *** p<0.01, ** p<0.05, * p<0.1

Table VII, columns (1) and (2) presents the results for the value equation (1), correcting for selection bias using the equation in Table VI. We start by using *Highest_economic_impact* as our dependent variable, and opt for a probit model, Column (1) reports the marginal effects relative to the value equation. The coefficient of *Collaboration,* which indicates whether the invention involved collaboration with a university, is positive but not significant. Column (2) distinguishes between personal contracts with an academic (*PContract*) and institutional contracts (*Institutional*): the coefficient of the former is bigger than the coefficient of the latter; however, in both cases the coefficients are not significantly different from zero.

Table VII column (3) presents the results of the two-stage least squares (2SLS) estimations with personal contracts (*PContract*) instrumented by the three variables described in section 3.3. The 2SLS estimations do not account for selection bias. Our choice to use 2SLS is supported by the fact that in Table VII columns (1) and (2) the rho coefficient indicates lack of selection bias in the estimation of equation (1). The under-identification test of the first stage statistics shows that the excluded instruments are relevant, as shown also by the positive and significant coefficients of the first stage. In addition, the Hansen test suggests that the model is correctly identified, and the excluded instruments are not correlated to the error term.[17] Finally, the Angrist and Pischke (2009) test for weak instruments rejects the hypothesis of weak instruments. Here, *Pcontract* remains positive and its coefficient increases in size and becomes significant. The Wald test confirms that the coefficient of *Pcontract* is significantly larger than the coefficient of *Institutional*. The 2SLS estimates can be interpreted in terms of local average treatment effect (Imbens and Angrist, 1994): the increase in the size of the coefficient indicates that for the subsample of inventors whose treatment status is affected by the instruments, the effect of personal contracts is substantially greater than for the whole sample. In other words, using personal contracts leads to high value inventions especially when inventors choose them based on their relational proximity to academic researchers.[18]

[17] The validity of our IV estimates might be affected by the fact that having a technical education might be positively correlated to the value of the inventor's invention as in Toivanen and Vänänen (2016) for a large sample of Finnish inventors. If this is the case, *alumni_polito* may not be exogenous to the value of the invention. To check this we performed a difference-in-Sargan statistic which allows us to test a subset of the orthogonality conditions for specific regressors. The value of this test, performed specifically to check the exogeneity of *alumni_polito*, is 0.032 with a p-value of 0.857 which generally confirms the null-hypothesis of exogeneity of the instrument. We interpret this as confirmation that in our sample inventor's technical education does not substantially affect the value of his or her invention.

[18] Only 3% of cases (5 out of 164) involved both governance types used jointly. As an additional robustness check we ran our models excluding those 5 inventors: the results of the estimation did not change. Overall, this confirms that joint use of the two governance forms is rare and does not affect our results.

Table VII. Probit and IV on *Highest_economic_impact*

	(1) Probit with sample selection	(2) Probit with sample selection	(3) IV-2SLS
VARIABLES	*Highest_economic_impact*	*Highest_economic_impact*	*Highest_economic_impact*
Governance			
Collaboration	0.107		
	(0.083)		
Pcontracts		0.151	0.593*
		(0.098)	(0.309)
Institutional		0.023	0.097
		(0.094)	(0.102)
Inventor Characteristics			
Theories	0.167*	0.167*	0.152*
	(0.097)	(0.098)	(0.083)
Methods	-0.011	-0.008	-0.006
	(0.083)	(0.083)	(0.070)
Applied	-0.107	-0.107	-0.074
	(0.094)	(0.094)	(0.091)
Contact	0.075	0.068	0.060
	(0.095)	(0.094)	(0.085)
Age	-0.059**	-0.054**	-0.056**
	(0.027)	(0.026)	(0.023)
Age^2	0.001**	0.001**	0.001***
	(0.000)	(0.000)	(0.000)
Publications	-0.006	-0.006	-0.003*
	(0.004)	(0.004)	(0.002)
Male	-0.090	-0.105	-0.139
	(0.154)	(0.155)	(0.152)
Firm Characteristics			
Small and Medium Firms	0.016	-0.003	-0.071
	(0.172)	(0.172)	(0.179)
Large Firms	-0.140	-0.144	-0.231
	(0.159)	(0.162)	(0.166)
Technological capability	0.146**	0.142**	0.121*
	(0.071)	(0.071)	(0.065)
Technological dummies	***yes***	***yes***	***yes***
First stage			
Local			0.465**
			(0.199)
Alumni_polito			0.237*
			(0.122)
Share Italy			0.319**
			(0.153)
Wald test Pcontracts = Institutional		1.10	3.54
p-value		0.294	0.060
Underid. test (Kleibergen-Paap rk LM statistic):			9.097
p-value			0.028
Angrist-Pischke F test of excluded instruments:			4.04
Prob>F			0.008
Hansen J statistic (overid. test of all instruments):			0.075
χ^2 P-value			0.963
athanrho	-0.166	-0.139	-
	(0.411)	(0.402)	-
Observations	657	657	164
Uncensored obs.	164	164	-

Equations in columns (1) and (2) are estimated with a probit model with sample selection. The reference category for the size dummies are micro companies and individual inventors. In columns (1) and (2) marginal effects (at the sample mean) are displayed. In column (3) the coefficients of a 2SLS instrumental variable estimation are displayed, first stage coefficients are reported. All models include OST7-based technological dummies. Standard errors are robust to heteroskedasticity. *** p<0.01, ** p<0.05, * p<0.1

Among the control variables, the coefficient of *Theories,* which indicates that inventors use university knowledge in order to access scientific theorems and principles, is positive and significant. The coefficients of the other types of knowledge are not significant. The age variable and its squared term indicate a U-shaped relationship between age and the probability of achieving an economically valuable invention that has benefited from academic knowledge. More specifically, given the coefficients of age of -0.059 and of age squared of 0.001, we find that after 29.5 years of age the effect of age becomes positive, and increasingly more positive as age increases. The coefficient of *Publications* is negative, showing that higher levels of inventor engagement with scientific research do not increase the relative value of inventions with a high contribution of university knowledge. Firm size and especially large size, has a negative but not significant coefficient, while the coefficient of firm's technological capability is positive and significant, indicating that inventors working for R&D-active firms are more able to exploit university knowledge to create economic value. The model includes technology dummies (not reported in the tables), which are never significant.

Table VIII presents the results of a Tobit type II model (Amemiya, 1984) where the variable *Relative_economic_value* is the dependent variable in the value equation (the selection equation is reported in Appendix B). Table VIII column (1) shows that *Collaboration* is positive but not significant. Column (2) distinguishes between the two governance forms for collaboration; only personal contractual collaboration with an individual scientist (*PContract*) is positively (and significantly) correlated to the relative value of the invention with the highest contribution of academic knowledge, while institutional collaboration (*Institutional*) is negative but not significant. The Wald test on the difference between the two coefficients (at the bottom of table VIII) confirms that the coefficient of *PContract* is significantly larger than the coefficient of

Insitutional.[19] The rho coefficient is always positive and significant, meaning that for this specification we need the selection equation. Table VIII columns (3) and (4) present the results of the 2SLS estimation of equation (1) with *Relative_economic_value* as the dependent variable. Again, the results show that *PContract* is positive and significant when instrumented (and significantly different from the coefficient of *Institutional*). The first stage statistics with *Relative_economic_value* as the dependent variable show that while *Local* remains strongly relevant, the other two instruments lose most of their significance: this results in lower F-statistics and a potential problem of weak instruments. This is because using *Relative_economic_value* reduces the number of observations, and these missing observations are likely to include inventors whose treatment status is changed by the other two instruments (alumni effect and professional networks outside the region). The only instrument in column (4) is *Local*: the results do not change and we find that in this new specification the instrument is no longer weak, as shown by the F-statistic.

In this specification, the coefficients of *Theory* and of firm's *Technological capability* remain positive and significant. We find also that the coefficient of large firms is negative and significant, similar to the results in table VII. This negative effect of large firms is because they rely mostly on internal resources to innovate, in line with the "corporate model" of knowledge generation (Antonelli and Fassio, 2014). Therefore, it is less likely that collaboration with a university will lead to a relatively high economic impact invention by an employee of a large

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[19] Careful analysis of industry inventors' interactions with a university shows that the channels of interactions are often complex and involve different types of formal and informal collaboration simultaneously. Inventors indicated that frequently they exploited several organizational forms. Even if the question on the governance of interactions was focused on the different types of contractual arrangements, and hence did not include the full spectrum of informal types of interactions, we found that personal and institutional collaborations often occurred in tandem with supervision of masters and doctoral students, or use of shared university laboratory facilities. Given the numerous possible combinations of interaction forms we ran a principal components analysis (PCA) on all the types indicated by our inventors, and extracted some factors that represent stylized ways of interacting with a university. The results of the PCA identify three main components: the first corresponds to personal contractual collaboration, the second refers mostly to institutional collaborations, and the third refers to ways of benefiting from academic knowledge that do not involve direct interaction. When we included the three factors in our value equation we found that personal contractual collaborations was positive and significantly larger than the coefficient of the institutional type of collaboration, confirming the robustness of our preferred specification in tables VII and VIII.

firm. However, micro companies and engineering consultancies which usually do not possess all the competences needed to develop innovations, gain comparatively more from collaborating with a university, and their inventions developed with the contribution of academic knowledge will be more likely to be their most valuable inventions. Technology dummies (not reported in the tables) are weakly significant.

Table VIII. Tobit and IV on the *Relative_economic_value* of the two values

	(1) Tobit with sample selection	(2) Tobit with sample selection	(3) IV-2SLS	(4) IV-SLS
VARIABLES	*Relative_economic_value*	*Relative_economic_value*	*Relative_economic_value*	*Relative_economic_value*
Governance				
Collaboration	0.048			
	(0.088)			
Pcontracts		0.154*	0.464*	0.478*
		(0.093)	(0.275)	(0.279)
Institutional		-0.097	-0.028	-0.021
		(0.094)	(0.128)	(0.129)
Inventor characteristics				
Theories	0.180*	0.185**	0.187*	0.180*
	(0.095)	(0.091)	(0.096)	(0.097)
Methods	0.103	0.129	0.175*	0.186*
	(0.112)	(0.105)	(0.104)	(0.106)
Applied	0.009	0.004	0.021	0.022
	(0.105)	(0.105)	(0.122)	(0.122)
Contact	0.035	0.032	0.008	0.016
	(0.102)	(0.101)	(0.109)	(0.112)
Age	-0.040	-0.042	-0.049	-0.050
	(0.040)	(0.040)	(0.040)	(0.043)
Age^2	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Publications	-0.003*	-0.003	-0.003	-0.003
	(0.002)	(0.002)	(0.002)	(0.002)
Male	0.192	0.229	0.259	0.252
	(0.271)	(0.239)	(0.238)	(0.234)
Firm Characteristics				
Small and Medium Firms	-0.100	-0.166	-0.213	-0.211
	(0.164)	(0.169)	(0.186)	(0.181)
Large Firms	-0.245	-0.300*	-0.371*	-0.380**
	(0.155)	(0.164)	(0.192)	(0.192)
Technological capability	0.148*	0.156**	0.127**	0.128**
	(0.076)	(0.067)	(0.061)	(0.062)
Technological dummies	***yes***	***yes***	***yes***	***yes***
First stage				
local			0.795***	0.688***
			(0.202)	(0.184)
alumni_polito			0.334	-
			(0.203)	-

Share Italy			0.116	-
			(0.224)	-
Wald test Pcontracts = Institutional		4.85	5.37	5.41
p-value		0.027	0.020	0.020
Underid. test (Kleibergen-Paap rk LM statistic):			6.262	3.996
p-value			0.099	0.045
Angrist-Pischke F test of excluded instruments:			4.94	14.00
Prob>F			0.004	0.00
Hansen J statistic (overid. test of all instruments):			0.113	0.912
χ^2 P-value			0.945	0.633
athanrho	0.827*	0.743**	-	-
	(0.488)	(0.356)	-	-
Observations	580	580	87	87
Uncensored obs.	87	87	-	-

Equations in columns (1) and (2) are estimated with a Tobit Type II model with sample selection. The reference category for the size dummies are micro companies and individual inventors. In columns (3) and (4) the coefficients of a 2SLS instrumental variable estimation are displayed, first stage coefficients are reported. All models include OST7-based technological dummies. Standard errors are robust to heteroskedasticity. *** p<0.01, ** p<0.05, * p<0.1

Overall, the results suggest the existence of a positive causal effect of personal contractual collaborations on the relative value of an invention developed with the contribution of university knowledge which is in line with our hypothesis, while institutional collaboration does not have an effect on invention value.[20]

Robustness checks: the role of academic co-publication

Alternative informal channels of interaction between industry inventors and university researchers such as co-authorship of academic papers, might influence the overall economic value of inventions. Gittelman and Kogut (2003) suggest that this is an important source of

[20] For some inventions we were able to identify the registered EPO patent of the invention with highest university contribution. We have hence run an additional robustness check of our specification using as the dependent variable the number of years for which the renewal fees were paid for each patent (controlling for the date of publication of the patent). This measure is a good alternative to our own measure of economic value and it is a better proxy than forward citations, which instead capture better the technological relevance of a patent (see also Harhoff et al., 1999; Arts and Fleming, 2018). Our results show that, even if we can only perform this estimation on 117 patents (those for which we were able to identify the correspondent EPO patent), the results are in line with our measure of economic value: personal contractual collaborations still display a positive and significant coefficient, which is also significantly larger than the coefficient of institutional collaborations. Results are available from the corresponding author upon request.

academic knowledge for industry. To check this we collected the number of co-publications in Scopus involving the 164 industrial inventors in our main equation and academics.[21]

Table IX. Robustness checks: the role of academic co-publications

	(1) IV-2SLS	(2) IV-2SLS
VARIABLES	*Highest_economic_impact*	*Relative_economic_value*
Governance		
Pcontracts	0.561*	0.460*
	(0.316)	(0.277)
Institutional	0.085	-0.032
	(0.105)	(0.132)
Inventor characteristics		
Academic co-publications	0.010	0.003
	(0.009)	(0.009)
Publications	-0.006**	-0.004
	(0.003)	(0.004)
Theories	0.147*	0.185*
	(0.082)	(0.095)
Methods	-0.005	0.175*
	(0.070)	(0.104)
Applied	-0.078	0.019
	(0.090)	(0.123)
Contact	0.068	0.013
	(0.084)	(0.111)
Age	-0.054**	-0.049
	(0.022)	(0.040)
Age^2	0.001***	0.000
	(0.000)	(0.000)
Male	-0.142	0.255
	(0.151)	(0.234)
Firm Characteristics		
Small and Medium Firms	-0.078	-0.216
	(0.175)	(0.184)
Large Firms	-0.230	-0.370*
	(0.163)	(0.192)
Technological capability	0.109*	0.122*
	(0.060)	(0.065)
Technological dummies	***yes***	***yes***
First stage		
local	0.465**	0.809***
	(0.199)	(0.217)
alumni_polito	0.230*	0.313
	(0.120)	(0.194)
Share Italy	0.308**	0.117

[21] We identified publications in Scopus of inventors who coauthored academic papers, which allows us to identify academic co-authors and their affiliations.

	(0.154)	(0.224)
Wald test Pcontracts = Institutional	3.21	5.47
p-value	0.073	0.019
Underid. test (Kleibergen-Paap rk LM statistic):	8.738	4.81
p-value	0.033	0.044
Angrist-Pischke F test of excluded instruments:	3.85	6.17
Prob>F	0.011	0.10
Hansen J statistic (overid. test of all instruments):	0.058	0.129
χ^2 P-value	0.971	0.937
Observations	164	87

In column (1) the dependent variable is *highest economic impact* (dummy 0/1), in column (2) the dependent variable is *relative economic value*.In columns (1) and (2) the coefficients of a 2SLS instrumental variable estimation are displayed, first stage coefficients are reported. The reference category for the size dummies are micro companies and individual inventors. All models include OST7-based technological dummies. Standard errors are robust to heteroskedasticity. *** p<0.01, ** p<0.05, * p<0.1

Table IX presents the results obtained including this additional regressor among our control variables in the 2SLS instrumental variable regressions: the results point to a non-significant effect of the number of co-publications on the economic value of a patent, while the significant positive effect of personal contractual collaborations is still present. However, the first stage statistics of the IV estimation indicate that our instruments perform relatively worse than in our preferred estimation in tables VII and VIII. This is because the number of co-publications is partly correlated to the first stage instruments and our main variable of interest - *Pcontract*. It is possible that personal contracts lead to future co-publications. Another problem related to including the number of co-publications is that the economic value of an invention can affect future co-publications: a high economic value might boost them or might hinder them if secrecy conditions require non-disclosure of the knowledge produced. For these reasons co-publications is likely to be an endogenous variable (for which we would need to find additional instruments), thus we prefer the specification in tables VII and VIII.

5. Discussion

Since the mid-1990s, universities have been considered fundamental drivers of technological change and competitiveness in regional and national economic systems. The underlying assumption is that firms that interact with universities should be able to introduce more valuable innovations and increase their economic performance: however, little attention has been paid to *the type of contractual governance of* university-industry interactions that contribute most to the value of industrial invention. Analyzing the effectiveness of different forms of governance of university-industry interactions would add to our understanding of how academic knowledge is translated into real industrial products and could shed light on the most profitable ways of managing structured interactions between organizations aimed at innovation.

Overall, our empirical results show that the use of formal contractual interactions is correlated positively but insignificantly to the relative value of the invention. This result is not surprising given that, during the development of the invention, the inventors might have had other kinds of non-contractual interactions in parallel with (or in place of) contractual interactions, and therefore could have benefited from direct engagement with academics in one form or another, even in the absence of contractual arrangements. This is in line with several studies showing that companies use a mix of formal and informal interactions with universities depending on the objective and the content of the interaction (Abreu et al., 2008). However, the focus of our analysis is on the relative effect of different types of contractual governance on economic value. Here we are able to confirm that personal contracts between firms and individual academics, characterized by the firm's greater control over the collaboration's scope and objectives, increase the incentives for the academic to invest in translating university knowledge to allow its more effective integration in the firm's knowledge base and promote innovation. This highlights the importance of promoting academic knowledge integration with the firm's knowledge base through the development of firm absorptive capacity.

In order to maximize the social and economic impact of academic knowledge, universities need to manage their interactions with industry carefully, and ensure that institutional contracts do not replace but enhance and complement personal ones. Personal contracts are likely to lead to more valuable inventions, but they often build upon pre-existing social ties. These are not automatic; they require time and effort and can be affected by the involvement of the university institution. For example, if the university insists on intellectual property rights concessions, the firm may withdraw from the collaboration (von Proff et al., 2012). Hence, the university should pursue institutional collaborations with industry, but at the same time encourage the development of personal ties (based on alumni networks or past collaboration) between company inventors and academics, and allow academics to stipulate personal contracts if opportunities arise. There are specific situations in which institutional arrangements are especially beneficial. These situations might occur when the collaboration involves areas of research and scientific networks to which the firm does not have direct access and which are more distant from its knowledge. These types of collaborations tend to be explorative rather than exploitative and might benefit from the more open-ended definition of objectives in institutional contracts.

Our analysis points also to the type of academic knowledge that industrial inventors consider most relevant for the development of inventions. In our sample, invention value increased with the inventor's reliance on theoretical knowledge. This is in line with suggestions that the use of scientific knowledge allows for the production of more radical inventions, which have greater economic value. Using more applied academic knowledge does not exploit the specificity of academic research and therefore does not increase the value of resulting inventions compared with the value of the other inventions in the inventor's portfolio. Hence, particularly for industry inventors who are not themselves engaging in academic research like those in our sample (who have, on average, low publication count) using theoretical scientific knowledge can help them to raise the novelty profile of their inventions. R&D managers should perhaps consider involving in collaborations with universities those inventors that are better able to appreciate the usefulness of basic theoretical knowledge, since these individuals will be better able to exploit academic knowledge in an Edison-bridging fashion (Subramanian et al., 2013) to increase their ability to produce valuable inventions.

This study has some limitations. First, although our initial sample was relatively large, the information required to construct our dependent variables was available only for a smaller sample. Second, as in most studies that use survey data, our results could be, to some extent affected by common method bias. However, we have taken several steps to mitigate this risk.

The models include numerous variables from different sources than the PIEMINV survey (such as databases on academic publications, EPO patent data, balance sheet data from company registers). In the survey, the questions were of different types, with very few involving Likert scales; moreover, not many questions asked about inventors' perceptions, while many asked simple facts about the innovation process (such as the form of governance and source of funding used). Third, our sample only includes inventors from Piedmont, which allows for a substantial degree of consistency, but might mean that the results are not generalizable to other contexts. Piedmont is a relatively technologically advanced region with various industry specializations; it is possible that in areas with a different mix of economic activities the type of governance of interactions might have a different effect. The relatively limited geographic mobility of industry and academic inventors in the Piedmont region is likely to facilitate the formation of social links that lead to more fruitful personal contractual collaborations; these conditions may not apply to other contexts. In some contexts, certain arrangements (e.g., skilled innovation intermediaries) might have emerged to facilitate knowledge transfer and knowledge integration within institutional collaborations. Further studies in other contexts comparing the two forms of governance analyzed would shed light on this.

Fourth, the study focuses only on the invention with the highest contribution from academic knowledge: it would be interesting to see whether our results hold for inventions with more moderate levels of academic knowledge which in some cases, may account for most of the firm's invention portfolio. Lastly, this study should be seen as a first step opening up a broader line of research into the relative effects of different governance forms on invention value. The study contrasted two ways of research contracting between university and industry, but collaborations not involving direct research contracts occur in many other ways (for example, through informal interactions, joint supervision of graduates and sharing of research laboratories among many others). Further research could explore whether these other forms of collaboration, whether carried out in isolation or in combination with formal research contracting, affect the value of industry inventions, and particularly whether certain combinations of governance forms are particularly fruitful.

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APPENDIX A: The PIEMINV Survey

The PIEMINV questionnaire was administered in autumn 2009 and spring 2010. It was addressed to inventors and was designed to investigate various aspects of university-industry interactions in the Italian region of Piedmont, and to enable quantitative measurement of the local universities' contribution to the invention process. It asked for information on: (i) the individual characteristics of Piedmontese inventors; (ii) which channels are used most frequently for university-industry knowledge transfer; (iii) the forms of governance of interactions; (iv) inventors' motivations and objectives in using different interaction channels.

The questionnaire (presented in full below) has four parts asking for different types of information, for a total of 41 questions.

1. General information related to inventors (age, gender, education, mobility) and their inventive activity (age at first patent, office where patents were first filed, invention: innovation ratio).
2. Overall evaluation of the importance of university knowledge in the development of inventions and the relative importance of different interaction channels.
3. Evaluation of the effectiveness, frequency and nature of university-industry interaction channels used to pursue different firm objectives.
4. Assessment of the economic impact of university knowledge (this section only refers to two specific inventions for each inventor)

Additional information on patent technology classes was collected, to enable a better understanding of the technology in which each inventor is active. Technology macro-classes for each inventor were attributed using the most common technology class found in the inventors' patent portfolio.[22]

The questionnaires were administered to 2,916 industry inventors, obtaining 938 valid responses (response rate 31%). The following criteria were applied to decide inclusion in the survey[23]:

a) the person is named as 'inventor' on at least one patent application filed (for the first time or as an extension) with the EPO;
b) the patent application was filed with the EPO between 1998 and 2005;
c) the inventor's address on the patent application is a location in the Piedmont region.

[22] Classification by macro-technology classes is according to OST-DT7 (OST, 2004).

[23] Questionnaires were sent by email wherever possible; where email addresses could not be identified, or where paper based questionnaires were requested, these were delivered by ordinary mail with an option to respond on an online platform.

Although surveys are the only method to recover certain kinds of data on inventors and the inventive process, they have some shortcomings. Since the survey is inventor-based (and not firm-based), it does not necessarily include all the innovative firms in the Piedmont region. Moreover, since the sample is based on inventors of EPO patent applications, it is biased in favour of inventors employed in large firms. It must also be stressed that the survey is based upon *applications* for patents to the EPO in 1998 to 2005, regardless of whether they were granted or rejected. Finally the survey cannot completely rule out a possible underestimation of highly mobile inventors (which the patent literature claims are more productive on average), since inventor's addresses on patents are not updated. This problem was partly reduced by considering an eight-year time frame.

The governance of university industry relations

A specific question of the questionnaire asked inventors to indicate which type of governance was used for the invention with the highest level of university contribution (and for the invention with the highest economic impact). The question, reported below in Table A1, focused on specific contract-based type of arrangements, focusing in particular on the use of institutional research collaborations, as opposed to contracts with individual university researchers. In our analyses we classified interactions as collaboration (*Collaboration)* -i.e. whether the development of the invention involved any form of contract-based collaboration with a university scientist- if the inventor answered 'yes' to at least one of the answers 1, 2 or 3 of Table A1. Then we distinguished between different types of contract-based collaborations. We classified a contract-based collaboration as institutional (*Institutional)*, i.e. stipulated with a university institution, if the inventor answered 'yes' to at least one of the answers 1 and 2 of Table A1. Finally we classified interactions as personal contract (*PContract*) if the inventor answered 'yes' to answer 3 of Table A1. The inventors could also indicate other non-contractual types of arrangements: these included the supervision of masters or PhD students (answer 4), as well as the sharing of facilities such as labs or equipment (answer 5). It must be stressed that the inventors could indicate the joint use of different types of interactions.[24]

For a more detailed analysis of the PIEMINV survey see Cecchelli et al. (2012). The database is available upon request from the authors.

[24] The options provided to inventors concerning the non-contractual interactions clearly do not include the full spectrum of informal types of interactions, such as informal contacts, participation to academic conferences, reading of scientific publications or patents, co-authorship of academic papers, and possibly other types of interactions. However the design of the question was mainly aimed to collect detailed information on the modes of use of contract-based collaborations.

Table A1. Question from the PIEMINV survey: "did the inventive process include any of the following organizational arrangements?"

	Your invention with the highest contribution from university knowledge	Your invention with the highest economic impact
1. Institutional research collaborations between your company and the university (department, faculty, university, technology transfer office), *financed by the company*		
2. Institutional research collaborations between your company and the university, *financed through public funds* (regional, national or international)		
3. Personal contracts between your company and *individual university researchers*		
4. Collaborations based on co-supervision of Masters or PhD students		
5. Sharing facilities (e.g. laboratories, equipment) with the university		
6. None of the above		

APPENDIX B

Table B1. Correlation table

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Highest economic impact	1.000															
2	Relative economic value	0.727*	1.000														
3	Collaboration	0.069	0.024	1.000													
4	Pcontracts	0.107	0.122	0.562*	1.000												
5	Institutional	-0.009	-0.093	0.649*	-0.188*	1.000											
6	Theories	0.148	0.319*	0.002	-0.053	0.032	1.000										
7	Methods	0.018	0.091	0.061	0.022	0.032	-0.013	1.000									
8	Applied	-0.149	-0.104	-0.094	-0.034	-0.073	-0.223*	-0.140	1.000								
9	Contact	0.084	-0.066	0.029	0.038	-0.002	-0.144	-0.164*	-0.325*	1.000							
10	Male	-0.019	0.146	0.013	0.074	-0.032	0.137	0.025	0.136	-0.174*	1.000						
11	Age	0.003	-0.061	0.081	-0.042	0.141	-0.0651	0.038	-0.017	0.086	0.197*	1.000					
12	HEducation	-0.053	-0.285*	-0.042	-0.040	-0.008	-0.161*	-0.114	0.022	0.009	-0.162*	-0.258*	1.000				
13	University work experience	-0.005	-0.225*	0.106	0.151	0.014	-0.014	-0.068	0.119	-0.062	0.040	0.127	0.164*	1.000			
14	Publications	-0.080	-0.217*	0.138	0.045	0.100	-0.078	-0.060	-0.142	0.106	-0.001	0.128	0.184*	0.198*	1.000		
15	Academic co-publications	0.042	-0.097	0.200*	0.093	0.126	-0.032	-0.033	-0.084	0.032	0.001	0.080	0.192*	0.156*	0.775*	1.000	
16	Technological productivity	0.023	-0.147	0.094	0.116	-0.009	-0.233*	-0.122	0.006	0.112	0.072	0.179*	-0.016	0.049	0.117	0.172*	1.000
17	Micro firms	0.034	0.050	-0.079	-0.116	0.047	0.057	0.039	-0.113	-0.060	-0.054	0.055	-0.059	-0.031	-0.109	-0.113	-0.097
18	Small and Medium Firms	0.063	0.041	-0.137	-0.010	-0.172*	0.006	0.043	0.018	0.096	0.140	0.124	0.024	0.087	-0.036	-0.014	-0.061
19	Large Firms	-0.076	-0.070	0.169*	0.083	0.116	-0.0424	-0.063	0.057	-0.043	-0.085	-0.142	0.017	-0.054	0.101	0.086	0.115
20	Foreign Firms	0.008	0.077	0.104	0.162*	-0.060	0.021	0.0909	-0.061	0.025	0.048	0.056	-0.049	0.223*	0.119	0.086	0.038
21	Technological capability	0.103	0.116	0.060	0.028	0.095	-0.002	0.033	0.097	-0.089	0.082	0.001	0.081	0.082	0.111	0.185*	0.010
22	Local	0.036	0.146	0.181*	0.070	0.122	0.089	0.033	-0.003	0.001	0.056	0.169*	-0.346*	-0.083	-0.068	-0.0699	0.018
23	Alumni_polito	0.079	0.081	0.068	0.097	0.005	-0.013	-0.144	-0.138	0.075	-0.030	-0.054	0.173*	0.046	0.034	0.079	0.267*
24	Share Italy	0.082	-0.138	0.244*	0.197*	0.170*	-0.184*	-0.043	-0.107	0.081	-0.116	0.086	0.186*	0.105	0.263*	0.304*	0.144

Table B1. …continued

		17	18	19	20	21	22	23	24
17	Micro firms	1.000							
18	Small and Medium Firms	-0.135	1.000						
19	Large Firms	-0.529*	-0.768*	1.000					
20	Foreign Firms	-0.110	-0.109	0.1650*	1.000				
21	Technological capability	-0.159*	-0.221*	0.292*	0.064	1.000			
22	Local	0.072	0.016	-0.061	0.046	-0.050	1.000		
23	Alumni_polito	0.039	0.064	-0.080	-0.123	-0.084	-0.060	1.000	
24	Share Italy	-0.118	-0.034	0.106	-0.041	0.223*	-0.108	-0.082	1.000

Note: correlations are calculated for the 164 inventors included in the empirical estimation of equation (1). Asterisks indicate statistical significance at the 5% level.

Table B2. Probit with sample selection on *Highest_economic_impact* (full specification)

	(1) Selection equation	(2) Probit	(3) Selection equation	(4) Probit
VARIABLES	*Contribution*	*Highest_economic _impact*	*Contribution*	*Highest_economic impact*
Governance				
Collaboration	-	0.107	-	-
	-	(0.083)	-	-
Pcontracts	-	-	-	0.151
	-	-	-	(0.098)
Institutional	-	-	-	0.023
	-	-	-	(0.094)
Inventor Characteristics				
Theories	-	0.167*	-	0.167*
	-	(0.097)	-	(0.098)
Methods	-	-0.011	-	-0.008
	-	(0.083)	-	(0.083)
Applied	-	-0.107	-	-0.107
	-	(0.094)	-	(0.094)
Contact	-	0.075	-	0.068
	-	(0.095)	-	(0.094)
Publications	-	-0.006	-	-0.006
	-	(0.004)	-	(0.004)
Male	0.045	-0.090	0.045	-0.105
	(0.056)	(0.154)	(0.056)	(0.155)
Age	-0.022	-0.059**	-0.022	-0.054**
	(0.015)	(0.027)	(0.015)	(0.026)
Age^2	0.000*	0.001**	0.000*	0.001**
	(0.000)	-0.059**	(0.000)	(0.000)
HEducation	0.183***		0.183***	
	(0.035)		(0.035)	
University Work Experience	0.231***		0.231***	
	(0.073)		(0.073)	
Technological Productivity	0.013*		0.013*	
	(0.007)		(0.007)	
Firm Characteristics				
Small and Medium Firms	-0.077	0.016	-0.077	-0.003
	(0.059)	(0.172)	(0.059)	(0.172)
Large Firms	0.009	-0.140	0.009	-0.144
	(0.060)	(0.159)	(0.060)	(0.162)
Technological capability	-0.024	0.146**	-0.024	0.142**
	(0.035)	(0.071)	(0.035)	(0.071)
Technological dummies	***yes***	***yes***	***yes***	
Wald test Pcontracts = Institutional	-	-	-	1.10
p-value	-	-	-	0.294
athanrho	-0.166	-0.166	-0.139	-0.139
	(0.411)	(0.411)	(0.402)	(0.402)
Observations	657	164	657	164

Columns (2) and (4) report the results of the estimation of a probit model with sample selection, where the dependent variable is *Highest_economic_impact*. Columns (1) and (3) reports the coefficient of the selection equation, where the dependent variable is *Contribution*. The reference category for the size dummies are micro companies and individual inventors. In all columns, marginal effects (at the sample mean) are displayed. All models include OST7-based technological dummies. The selection equations also include a dummy for foreign ownership (*foreign*). Standard errors are robust to heteroskedasticity. *** p<0.01, ** p<0.05, * p<0.1

Table B3. Tobit with sample selection on the *Relative_economic_value* of the two values (full specification)

	(1) Selection equation	(2) Probit	(3) Selection equation	(4) Probit
VARIABLES	*Contribution*	*Relative_economic _value*	*Contribution*	*Relative_economic _value*
Governance				
Collaboration	-	0.048	-	-
	-	(0.088)	-	-
Pcontracts	-	-	-	0.154*
	-	-	-	(0.093)
Institutional	-	-	-	-0.097
	-	-	-	(0.094)
Inventor Characteristics				
Theories	-	0.180*	-	0.185**
	-	(0.095)	-	(0.091)
Methods	-	0.103	-	0.129
	-	(0.112)	-	(0.105)
Applied	-	0.009	-	0.004
	-	(0.105)	-	(0.105)
Contact	-	0.035	-	0.032
	-	(0.102)	-	(0.101)
Publications	-	-0.003*	-	-0.003
	-	(0.002)	-	(0.002)
Male	0.089*	0.192	0.089*	0.229
	(0.032)	(0.271)	(0.032)	(0.239)
Age	-0.014	-0.040	-0.014	-0.042
	(0.013)	(0.040)	(0.013)	(0.040)
Age^2	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
HEducation	0.117***		0.117***	
	(0.030)		(0.030)	
University Work Experience	0.218***		0.218***	
	(0.076)		(0.076)	
Technological Productivity	0.005		0.005	
	(0.006)		(0.006)	
Firm Characteristics				
Small and Medium Firms	-0.041	-0.100	-0.041	-0.166
	(0.046)	(0.164)	(0.046)	(0.169)
Large Firms	-0.060	-0.245	-0.060	-0.300*
	(0.052)	(0.155)	(0.052)	(0.164)
Technological capability	0.016	0.148*	0.016	0.156**
	(0.028)	(0.076)	(0.028)	(0.067)
Technological dummies	***yes***	***yes***	***yes***	
Wald test Pcontracts = Institutional	-	-	-	4.85
p-value	-	-	-	0.027
athanrho	0.827*	0.827*	0.743**	0.743**
	(0.488)	(0.488)	(0.356)	(0.356)
Observations	580	87	580	87

Columns (2) and (4) report the results of the estimation of a Tobit Type II model with sample selection, where the dependent variable is *Relative_economic_value*. Columns (1) and (3) reports the coefficient of the selection equation, where the dependent variable is *Contribution*. The reference category for the size dummies are micro companies and individual inventors. In columns (1) and (3), marginal effects (at the sample mean) are displayed. All models include OST7-based technological dummies. The selection equations also include a dummy for foreign ownership (*foreign*). Standard errors are robust to heteroskedasticity. *** p<0.01, ** p<0.05, * p<0.1