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Dynamic interactions between university-industry knowledge transfer channels: A case study of the most highly cited academic patent

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ABSTRACT

This paper examines the succession of formal and informal channels of university-industry knowledge transfer, and the local economic impact of their dynamic interaction. To do so, we investigate a highly cited university patent over an extended period of time through a case study methodology. Our work provides three fundamental insights. First, local economic impact can be achieved only after a complex, temporally unfolding sequence of interactions between formal and informal channels of knowledge transfer. Second, in the course of this dynamic interaction, knowledge generated during formal transfer activities may be transferred via informal channels. Third, the method developed can provide information on the variety of knowledge transfer channels related to highly cited patents.

1. Introduction

Knowledge transfer in university-industry interactions can be either 'formal' or 'informal', depending on the presence or absence of a contract (Vedovello, 1997). Informal channels involve access to the pool of knowledge embodied in the expertise and equipment, and as well as the technical and scientific capabilities and needs, training, recruitment and/or allocation of qualified manpower in universities or firms in the absence of a contract. Formal channels imply contractually regulated exploitation of the knowledge, expertise and equipment available in universities and firms.

The study of formal and informal channels of knowledge transfer between university and industry has a long intellectual history in the field of Economics of Innovation (see Mowery and Ziedonis, 2015, for a recent literature review). Since the US Bayh-Dole act, which allowed US universities to register and license patents from public research, numerous studies have examined the licensing of university patents as a formal mechanism of knowledge transfer between universities and industry (Mowery and Sampat, 2005; Grimaldi et al., 2011). Other formal channels, such as consulting (Roessner, 1993), have also been analysed. Informal channels studied include personal contacts between academic and industry researchers (Cohen et al., 2002; D'Este and Patel, 2007; Bekkers and Freitas, 2008; Ramos-Vielba and Fernández-Esquinas, 2012).

Nonetheless, less attention has been paid to the temporally unfolding, dynamic relationship among channels of knowledge transfer. One partial exception is the work by Faulkner and Senker (1994), who acknowledge the existence of temporal continuity among formal and informal channels, reporting that 'informal linkage is often both precursor and successor of formal linkage' (p. 680). Similarly, D'Este and Patel (2007) show that researchers with previous experience of one knowledge transfer channel are more likely to be involved in transferring knowledge through other types of channels in the future. Rappert et al. (1999) find that informal contacts among university and industry actors can create the trust necessary for formal engagement. However, this was not the focus of their work and was not further developed. Most of these works recognize a dynamic interaction among transfer channels without providing more detail, and they do not address the relationships in a temporal sequence of channels, i.e. whether the knowledge trans-

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ferred by one channel is related to the knowledge transferred using other channels.

Moreover, almost no empirical research deals with the relationship between the dynamic interactions of formal and informal channels and the localization of their economic impact. The assumption of these studies is that knowledge transferred through one channel has no relationship with knowledge transferred through other channels. A corollary of this assumption is that the study of local economic impact can be limited to only one transfer channel. However, this does not mean that the localization of formal or informal channels has not been studied in the literature. For example, there is some consensus that informal knowledge transfer from universities has a more pronounced impact on the local industry since it often depends on personal communication and social connections among inventors which are more sensitive to distance (Breschi and Lissoni, 2001; Singh, 2005). There is less unanimity regarding formal channels. Some studies show the importance of proximity in formal transfer channels such as licensing (Agrawal, 2006) and R&D contracts (Rosa and Mohnen, 2008). Others, such as Audretsch and Stephan (1996, p. 651), find that 'when knowledge is transmitted through formal ties between researchers and firms, geographic proximity is not necessary, since face-to-face contact [. . .] is carefully planned'. Nevertheless, few studies compare the localization of formal and informal channels. Mowery and Ziedonis (2015) compare the local impact of university patent licences and citations to university patents among three top US universities and find that formal knowledge transfer (patent licensing) is more geographically localized than knowledge transfer based on patent citations, but the authors do not disentangle the channels underlying patent citations. Survey-based studies find opposite results: either formal knowledge transfer channels can be more localized than informal channels (Arundel and Geuna, 2004), or the other way round (De Fuentes and Dutrénit, 2014). Nonetheless, they use cross-sectional data and do not account for a temporally unfolding, dynamic interaction among channels which would require a longitudinal analysis. To our knowledge, longitudinal studies addressing the localization of knowledge transfer are reserved for work on the evolution of patent citations, which show a decline in localization over time (Jaffe et al., 1993). Meanwhile, the localization of economic impact of a temporal sequence of knowledge transfer channels is left unexplored. In this paper we are interested in capturing the moment in a temporal sequence of knowledge transfer channels when the economic impact becomes local.

To address these gaps, we exploit a little used but promising case study methodology to examine the channels of knowledge transfer related to a highly cited university patent, being our research questions: Is the knowledge transferred by one channel related in any way to the knowledge transferred by previously used channels? At which moment in a temporal sequence of channels does economic impact become local?

2. Case studies of highly cited university patents

The economic and technological importance of highly cited patents has been recognized following the pioneering work of Trajtenberg (1990) (see Barberá-Tomás et al., 2011 for a recent discussion). Jaffe et al. (1993, p. 597) highlight that case studies of highly cited patents can provide a more profound understanding of knowledge transfer:

> In future work we plan to identify a small number of patents that are extremely highly cited. It is likely that such patents are both technologically and economically important. Case studies of such patents and their citations could prove highly informative about [. . .] the mechanisms of knowledge transfer.

There is one highly cited university patent which has attracted the attention of researchers: the Cohen-Boyer 'Process for producing biologically functional molecular chimeras' (US4237224) based on recombinant DNA. The patent was applied for in 1974 by Stanford University and granted by the US Patent and Trademark Office (USPTO) in 1980. Feldman et al. (2007) provide a qualitative case study analysing the licensing strategy in the Cohen-Boyer patent and stressing the role of Stanford's Office of Technology and Licensing in flexibly managing this formal knowledge transfer channel. Feldman and Yoon (2012) study knowledge transfer, based on quantitative analysis of citations to this patent, and conclude that it has been used as a 'general purpose technology' by citing inventors who have built on the general recombinant process with applications in several domains. The richness of these findings suggests the variety of formal (notably licensing) and informal channels underlying knowledge transfer measured via patent citations.

Even more interesting in our context is a study of the Cohen-Bayer patent by Hughes (2001) in the discipline of the History of Science (Martin, 2012). Hughes demonstrates that in-depth, qualitative study of a highly cited patent could provide information on licensing and citations and also on other knowledge transfer channels. Although her main interest was not in temporally unfolding dynamic interactions and the localization of knowledge transfer channels, her narrative shows that the start of the patent application process in 1974 was followed in 1975 by a highly localized knowledge transfer channel: Cohen's consulting activity with the Cetus Corporation, a Bay Area company. Hughes (2001, p. 562) discusses the importance of the relationship between the knowledge transferred through the two channels of patenting and consulting:

> What raised concern in Cohen's case was the fact that he was an inventor on a Stanford patent application and at the same time a paid consultant for a company seeking a license on the invention being patented. He tried to reassure critics by arguing that he expected to be able 'to effectively separate my relationship with Stanford as the Inventor, from my relationship with Cetus as a scientific consultant', it was a fine–if not impossible–line that Cohen attempted to draw between Cohen the scientist, Cohen the inventor and Cohen the corporate consultant. . . Attempts to draw boundaries between the three interlocking realms were artificial and ultimately futile.

We extend Hughes' (2001) insights on the relationship between the knowledge transferred through the dynamic interactions among various channels and their localization, with a case study of a highly cited university patent over a long period of time. Case study research is used to examine the complex, context-dependent nature of processes, such as university-industry knowledge transfer, through in-depth examination of specific examples (Eisenhardt, 1989; Patton, 2005). Case studies are appropriate for exploratory research on previous unexamined phenomena (Eisenhardt, 1989) and, especially, phenomena which unfold over a prolonged period of time (Yin, 2013).

3. Methodology

Although the Cohen-Boyer patent has been identified as the most highly cited biomedical patent granted between 1976 and 1980 (Feldman and Yoon, 2012), the original interest of the qualitative case studies conducted by Feldman et al. (2007) and Hughes (2001) seems not to be its citation record, but the public importance of the patent in the history of biotechnology. In our case, we started by identifying the most cited patent in university patenting history (we had some hope that the methodology would not identify the Cohen-Boyer patent, since it had already been the subject of sev-

Table 1
Identifying highly cited university patents.

Publication number	Applicant	Citing documents (IPTS database)	Citing documents (Espacenet 30/4/2013)
DE19544207	Univ Dresden Tech [DE]	8	60
EP0601812	Univ Bristol [GB]	10	12
GB2104391	Univ Exeter [GB]	8	28
US4618861	Cornell Res Foundation Inc [US]	9	68
Focal patent	**West Coast University [US]**	**10**	**430**
US5177685	Massachusetts Inst Technology [US]	9	342
US5262871	Univ Rutgers [US]	8	429
US5561054	Univ Michigan State [US]	12	33
US5764190	Univ Hong Kong Science & Techn [HK]	14	109
US5770645	Univ Duke [US]	8	88
US5799055	Univ Northwestern [US]	9	110
US6737447	Univ Akron [US]	8	37
WO9428139	Massachusetts Inst Technology [US]	29	74

eral previous studies). We collected information and evidence from multiple sources (as is usual in case studies, George and Bennett, 2005) and analysed it in light of our interest in the dynamic interactions among and localization of formal and informal knowledge transfer channels. Although patents usually are related to transfer channels such as licensing, Hughes (2001) shows that highly cited patents can provide information on other channels of knowledge transfer. Thus, we widened our focus to include all possible knowledge transfer channels.

To identify the university patent with the most outstanding citation record we relied on a purpose-built dataset (based on PATSTAT and the Web of Science) created by the Institute of Prospective Studies (IPTS), which covers European Patent Office (EPO) applications by EU27 applicants in the period 1990–2007, with citations codified by type of organisation (e.g. university or industry). Other published works assess the validity of this source and provide details on its construction (e.g. Acosta et al., 2016).

The data include over 24,000 citations to university patents (67%) and papers (33%), which represents 1% of total citations. We identified the most frequently cited patents (Table 1). The number of citations is small due to the limited scope of the database (only direct EPO patents, only EU27 applicants, period 1990–2007, etc.). To ensure the identification of the most cited patents, we double-checked against the number of citations in the EPO webpage Espacenet, which offers a broader (worldwide) coverage.

The most cited patent (thereafter 'the focal patent')[1] was filed by an important West Coast university (thereafter 'the West Coast University') at the USPTO in 1989. Despite it being a younger patent than the Cohen-Boyer patent, its importance is exemplified by its 430 citations compared to the 342 citations to the Cohen-Boyer patent. The focal patent deals with a specific form of microsensors and actuators known as Micro-Electromechanical Systems (MEMS), based on the operating principle of electrostatic force. We conducted a quantitative study of forward citations to the patent (source: PATSTAT, October 2012 edition; 375 citations, not restricted to USPTO patents). We used our own elaboration of PATSTAT and occasionally USPTO data, in various ways, to answer some of the questions which arose during the research processes and which are detailed in Sections 4 and 5.

We performed a search in Google Scholar to obtain secondary data on our patent.[2] Firstly, we used a set of keywords including inventor names ('Inventor 1' and 'Inventor 2'), as well as the acronym defining the technology ('MEMS'), combined with 'history' and 'patent'. This search identified 2250 documents (books, theses, papers, reports, etc.). After checking the first 50 registers using Google Scholar's relevance algorithm, we refined our search to reduce overlaps arising from our use of MEMS, which includes a broad group of mechanical and electrical devices in the micrometer size range. Secondly, we searched on the keywords 'Inventor 1'+ 'Inventor 2' + 'MEMS' + 'sensors and actuators' + 'resonant microstructures' + 'patent'; which resulted in 344 documents. Then we examined the first 100 registers comparing the results obtained with both strategies. Thirdly; we obtained information on the historical context of the focal patent from five books; a doctoral thesis; one paper and three reports on MEMS; being our principal sources Rudolf et al. (1995), Bryzek (1996), Trimmer (1996), Judy (2001), and Howe et al. (2003).[3] The remaining documents were disregarded because they only referred to technical aspects; MEMS properties and applications; and not to information useful for our analysis.

After acquiring this preliminary 'scientific understanding of the field [. . .] by self-education [. . .] at the beginning of the empirical study' (Laudel and Gläser, 2007, p. 95), between July 2013 and January 2016 we conducted four in-depth 'informed interviews' with Inventors 1 and 2 (both professors of engineering in US West Coast universities) of our focal patent, and also with an renowned researcher in the same field, who was a long-term collaborator of one of the patent inventors and also the director of the research institute of the West Coast University (thereafter 'the Advanced Institute') during the period in which the research that resulted in the patented invention was conducted. The interviews were recorded and transcribed, and were followed up with emails to resolve specific questions which arose from our reading of the transcripts. During the interviews, we showed the interviewees representations of data about the focal patent derived from our patent databases, similar to Figs. 1 and 3 in this paper. Gläser and Laudel (2015, p. 310) state that graphical representations contribute, on several levels, to the informational yield from interviews: they demonstrate the efforts made by the interviewer and help to build trust; they contribute to creating a favourable atmosphere by confronting the interviewee with a new perspective on his or her work (i.e. the interviewer is not only asking for information but also is providing some); and they favour 'graphic elicitation', that is, they prompt narratives about the content of research, and trigger memories. Interviews concerning events which occurred several years earlier can be difficult if interviewees are unable to recall the events. Graphic representations help interviewees to reconstruct the evolution of the events.

[1] As agreed with the interviewees, names of individuals and organizations have been anonymized.

[2] Although criticized as a potential evaluation tool (Norris and Oppenheim, 2007), Google Scholar is particularly appropriate for identifying reviews in social sciences and humanities when exploring a diversity of sources including academic papers, handbooks, 'grey' literature and technical reports (Torres-Salinas et al., 2009; Prins et al., 2016).

[3] We use also other two sources about the history of the institutions we study that we skip here to preserve anonymity, and which informed mainly Section 5.3.

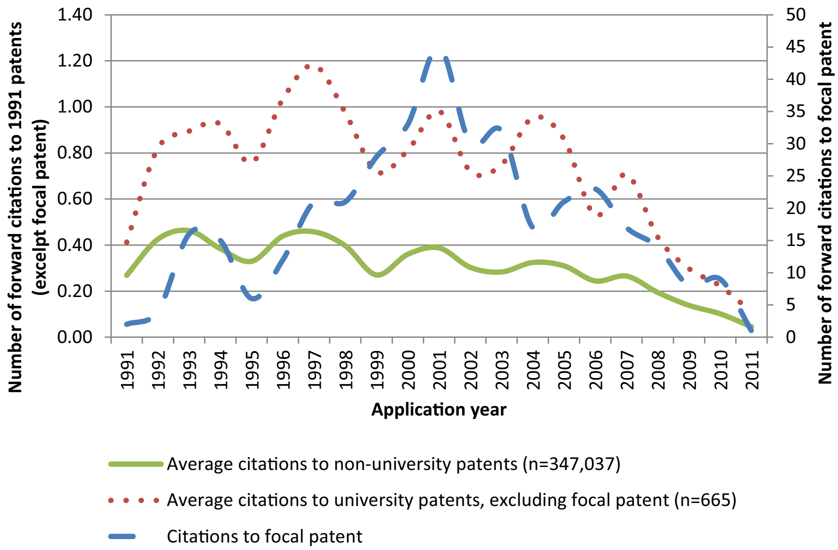

Fig. 1. Evolution of forward citations to the focal patent and its 1991 cohort patents.
Source: own elaboration of PATSTAT data.

We also conducted email interviews with inventors in the top three firms of the university's region based on number of citations to the focal patent (they accounted jointly for 75% of all local applicant citations). The advantages and disadvantages of email interviews have been discussed in the literature (Hamilton and Bowers, 2006; Meho, 2006). The advantages include equivalency of context for both researcher and participant, shift of expertise to participant, time for both researcher and participant to reflect on the question(s), co-occurrence of analysis with questioning, easily maintained audit trail, and increased external reliability. The disadvantages include potentially increased risk of loss of confidentiality, loss of spontaneity and visual cues and loss of silence as an interpretive moment. The superiority of traditional face-to-face interviews over email interviews is not clear (Hamilton and Bowers, 2006). Although mixed-mode interviewing (as in our case) is preferable to email interviewing only, the latter can be acceptable (Meho, 2006) and appropriate for complex questions (Abels, 1996). The disadvantages of email interviews are minimized in communities where use of the email is extensive (Morgan and Symon, 2004), as in our case.

Between November and December 2015, we contacted five inventors via email. Four of the respondents (labelled Inventors A–D) included the top three individual citers. One was employed in a subsidiary of the firm at the time of invention located outside the university's region, but was a former Advanced Institute student, and provided information on local and non-local channels. The fifth inventor replied, but could not remember the source of the citation.

4. The focal patent: technical and historical context

As already mentioned, the focal patent deals with a specific form of microsensors and actuators known as MEMS, based on the operating principle of electrostatic force. This force is sufficiently large at the nano and micro levels to produce relative movements between the elements of the devices, which then are capable of identifying an alteration in the environment (sensor), or transforming an alteration in a physical movement (actuator). Previous engineering efforts were aimed at reducing size and power while simultaneously increasing the performance of a diverse set of electromechanical systems. MEMS have radically transformed the scale, performance and cost of these systems by employing batch-fabrication techniques and achieving economies of scale, which have been exploited successfully by the micro-electromechanical industry (Bryzek, 1996; Trimmer, 1996; Judy, 2001). Specifically, MEMS technology enables order of magnitude reductions in the size of many types of sensors, actuators and systems while improving their performance (e.g. inertial sensors, optical switch arrays, biochemical analysis systems, etc.). Appendix Table A1 presents some principal milestones in the history of MEMS.

The focal patent was developed during a period (the late 1980s) when the field of MEMS was starting to coalesce in a coherent manner: the terminology used was homogenized and practical application of the knowledge advanced:

> Before MEMS was named in 1987–we kind of named the field–in Europe it would be microsystems. Nano systems in the US is MEMS or NEMS, and in Asia [. . .]. But in the '80s. . . people were beginning to think of things that were beginning to be more manufactureable.
>
> Inventor 2.

It should be noted that this coalescence was contested since, in this early stage, the field lacked legitimacy (Powell and DiMaggio, 2012) especially in industry. Researchers, many times, had to play the role of 'institutional entrepreneur' (DiMaggio, 1988), organizing 'field configuring events' such as conferences (Lampel and Meyer, 2008), and promoting new specialist journals:

> The spirit was very, very much a bunch of very courageous pioneers all doing something that they loved and they had no idea if it was going to be a big success or a small success or anything else like that. . . Imagine a world in which companies will laugh when they first heard of it: 'Ah, MEMS··· what a stupid exercise that will never have any practical purpose' [. . .]. If you wanted to make a big contribution in MEMS it was insufficient just to do the research. You had to help organize conferences and you had to convince journals that they wanted to publish these papers. You had to help form your own journal, which is one of the activities I was involved in the process of foundation of the MEMS journal.
>
> Advanced Institute Director.

In this context, the institutional configuration of partners of the Advanced Institute was crucial for ensuring industry commit-

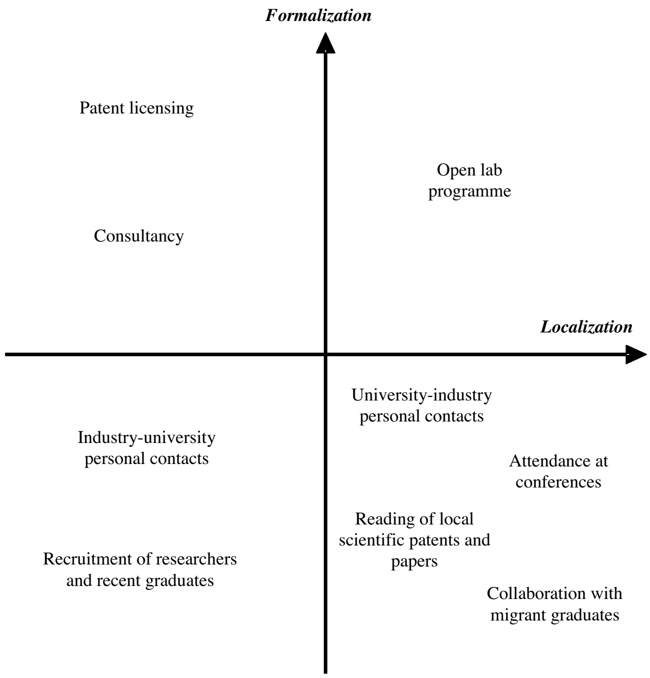

Fig. 2. Localization and formalization of knowledge transfer channels linked to the focal patent.

ment. The Advanced Institute was founded in 1986 and exemplifies the 'triple helix' of industry, university and government (Etzkowitz and Leydesdorff, 1995): it received funding from the National Science Foundation (a US Federal Government institution) and several industry partners to conduct research on MEMS. Since its foundation, the Advanced Institute's policy has been to perform research with industry relevance. The Advanced Institute made extensive use of the West Coast University's microfabrication laboratory (thereafter 'the Microlab'), which plays a major role in this case study.[4]

The patent was one of the first granted to the West Coast University after the passing of the Bayh-Dole Act, in a context of major institutional changes oriented to increase the patenting propensity of universities (Caballero and Jaffe, 1993; Colyvas et al., 2002). One of the inventors of the patent reported that, without this legal change, the application would probably not have emerged. The West Coast University's Technology Transfer Office (TTO) generally did not officially inform inventors of the identity of licensees: they just issued the royalty cheques. This is a limitation in our licensing data: the inventors provided information on the identity and number of licensees based on informal contacts with the TTO and on the evolution of their royalties.

The patent became known in the field as the 'comb drive' patent because of the shape of the actuator. The knowledge embodied in the patent was the result of the PhD thesis of Inventor 1, which was supervised by Inventor 2, and was conducted in the Advanced Institute from 1986 to 1990, with funding from the 'Emerging Technologies Initiative' of the US National Science Foundation. Verhoeven et al. (2016) have proposed three 'ex ante' indicators which could predict the technological importance of a patent: novelty in recombination, in technological origin, and in scientific origin. They computed the values for our focal patent, and found that it scores high for novelty in recombination (it originated five combinations) and in technological origin, but not in scientific origin. Scoring high for two categories, and originating five new combinations is rare, so the focal patent can be seen as highly novel based on these measures.

Fig. 1 shows an increase in the number of citations to the focal patent during the first ten years, with a peak in 2001 followed by a decrease. The ongoing discussion on the value of patent citations (Trajtenberg, 1990; Harhoff et al., 1999; Gambardella et al., 2008) characterizes citations as indicators of economic or technological value (Wartburg et al., 2005; Barberá-Tomás et al., 2011). Feldman and Yoon's (2012) study of the Cohen-Bayer patent suggests that a high number of citations could be due to the potential for the invention to be 'integrated with a wide range of industrial applications' (p. 54).

When asked about the technological importance of the patent, all our informants pointed out that it enabled linear movements rather than the circular ones allowed by previous generations of MEMS. This permitted the creation of (or improvements to) a broad range of applications from airbags to printers, or to sensors measuring blood pressure (Rudolf et al., 1995). One of the inventors of a local firm with patents citing the focal patent said that:

> [The] patent was a core reference for those like myself who wanted to use comb drives in our particular invention.
>
> Inventor A.

Thus, the 'ex post' technological importance of the focal patent seemed to lie in the new possibilities that linear movement at the nano and micro levels offered for MEMS development. A historical comparison provides a better understanding of the importance of this achievement. Cardwell (1995) describes one of the most important elements of Watt's steam engine as its ability to perform linear movements. Watt's 'parallel linkage' was widely adopted in different applications in industrial and mining machinery, automobile suspensions, locomotives and metering devices.

5. Knowledge transfer channels related to the focal patent

In this section we describe the knowledge transfer channels linked to the comb drive patent. Although, as already discussed, patents are related intuitively to formal channels such as licensing, we tried to identify all possible knowledge transfer channels that might be involved. Fig. 2 is a visualization of the heuristic approach guiding our enquiry: knowledge can be transferred through formal and local channels (upper right quadrant), informal and non-local channels (lower left quadrant), or intermediate combinations (remaining two quadrants). We chose this representation as a heuristic device to develop our findings for two reasons. First, it captures two crucial dimensions of our framework–formalization and localization. Second, it allows us to show graphically the variety of knowledge transfer channels related to the comb drive patent, and their different characteristics.

5.1. Formal channels, low localization

This quadrant includes patent licensing, which is a formal knowledge transfer channel. In our case, the only licensee was from a different region to the patenting university. The Advanced Institute received funding from the National Science Foundation and several industry partners, which paid annual fees for priority licensing of the new technologies developed by the Advanced Institute. Studies analysing university patent licensing and localization generally conclude that licensees located near universities may be better positioned to exploit knowledge transferred through licensing contracts (Mowery and Ziedonis, 2015, p. 54). However,

[4] The Microlab was founded in 1983. In 1986, the sensor research group (part of the Advanced Institute and including Inventors 1 and 2) became the lab's largest constituency and remained so throughout the life of Microlab. Although Microlab closed in 2010, research continues in the University's Nanofabrication Laboratory.

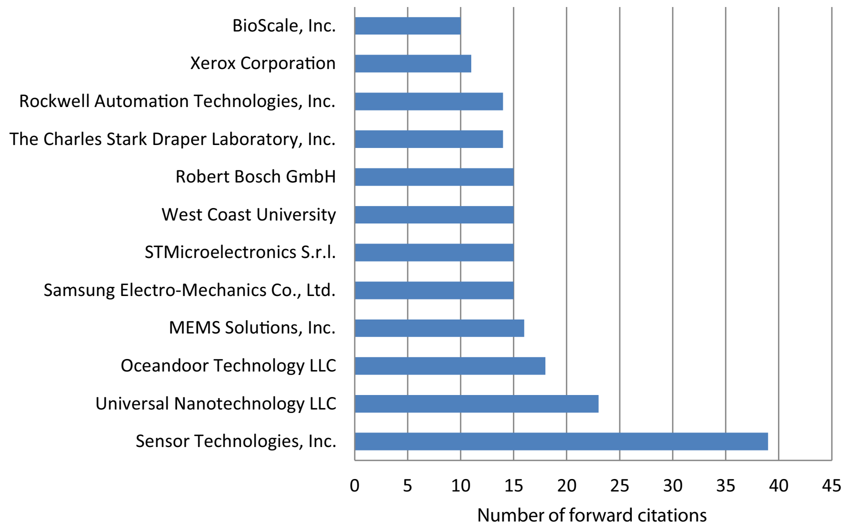

Fig. 3. Top applicants citing the focal patent, 1991–2011 (the top 4 names are anonymized). Total citations = 375, duplicated if more than one applicant per patent (full count = 439).
Source: Authors' elaboration from PATSTAT data.

during the early years of the Advanced Institute, the MEMS industry was in its infancy and there were no MEMS companies based in the West Coast University's region: the Advanced Institute's five original industry partners were on the East Coast or in the Midwest.

After the patent expired, its inventors felt it had failed to provide substantial royalty earnings; according to one inventor, '*at the peak, it was 2% of my full income*'. MEMS Solutions is one of the most frequent citers of the focal patent; however, despite being the only company to which the patent was licensed (in 1999), it is ranked only fourth for citations (Fig. 3). The first ranked is Sensor Technologies, another original industry partner of the Advanced Institute. Both Sensor Technologies and MEMS Solutions are large, successful, international companies, which fits with the findings from previous work that this type of firm is well-suited to absorption of academic research results, regardless of location (De Fuentes and Dutrénit, 2014).

Sensor Technologies, which is located in a different region from the patenting university, employed an alternative channel, contract consultancy, which by nature is formal and, in this case, was not localized. In 1988, when the research related to the focal patent was ongoing, the second inventor became involved in various consultancy projects with Sensor Technologies related to the MEMS technology. Part of this collaboration included the conceptualization of MEMS designs which could be produced in both Advanced Institute's and Sensor Technologies' laboratories.

It is difficult to determine exactly the relationship between the knowledge transferred through this channel and the knowledge embodied in the focal patent. While Inventor 2 disconnects his consultancy for Sensor Technologies from the patent *('this [was] not the comb drive thing*'), Inventor 1 saw the consultancy work of Inventor 2 as broadly related to the comb drive technology. The Advanced Institute Director explained how Sensor Technologies started to use the comb drive technology during the early 90s, very soon after the granting of the patent, and acknowledged the similarities with the Advanced Institute developments. He also related Sensor Technologies' early efforts with its collaboration with Inventor 2:

> Sensor Technologies jumped on very early. The first Sensor Technologies accelerometer came out in 1992, maybe? Almost parallel with [the Advanced Institute research on comb drives], Sensor Technologies came out with an accelerometer that used comb drives [. . .]. They used the comb drive this way, we were using it this way [. . .]. After we got the fundamental comb drive motor stuff going [. . .] then Inventor 2 started working very closely with Sensor Technologies.
>
> Advanced Institute Director.

Table 2
Sensor Technologies and Inventor 2.

Applicant	Inventor 2 self-citations	Other citations	Total
Sensor Technologies	5	34	39
West Coast University	9	6	15
Total	14	40	54

Source: own elaboration from PATSTAT.

When asked specifically about the reasons of the similarities between Sensor Technologies' accelerometers and a patented (but not licensed) technology, he pointed out to the close relationship between the company and the Advanced Institute and again more concretely to the relationship with Inventor 2.

> Sensor Technologies was a member of our centre and they saw everything that we did. . . Inventor 2 worked with them very intimately. He may or may not have had a consulting role with them as well as a research role.
>
> Advanced Institute Director.

In fact, as Inventor 2 recalled, the TTO of the West Coast University at some point considered that the design of one of Sensor Technologies' accelerometers, developed in the early 1990s, was very similar to the comb drive patent, and that Sensor Technologies should obtain a patent licence from the West Coast University. The TTO asked the opinions of Inventor 2 and other researchers since they thought that Inventor 2 might be influenced by his consultancy relationship with Sensor Technologies:

> They thought because I was consulting for them that I was, 'Oh, you know. These are my friends. They gave me a secret payment in the Bahamas or the Cayman Islands or something and yeah, I don't want to sue them'.
>
> Inventor 2.

Ultimately, the TTO neither sued Sensor Technologies nor required it to license the patent; Inventor 2 said that this was

Table 3
National and international forward citations to focal patent.

Applicant world zone	Number of forward citations	%	Excluding applicant and inventor self-citations	%
International	164	37.4%	164	39.4%
US, except region of West Coast University	164	37.4%	159	38.2%
Region of West Coast University	80	18.2%	65	15.6%
US, unknown region	31	7.1%	28	6.7%
Total	439	100.0%	416	100%

Source: Authors' elaboration of PATSTAT data.

because the design knowledge[5] embodied in the patent was not sufficiently similar to that contained in Sensor Technologies' artefact. Although the shape of Sensor Technologies' accelerator was similar to the shape of the patented comb drive, the accelerator's movement was different from the linear movement of the comb drive due to the introduction of an electronic loop. It should be noted, that in Inventor 2′s opinion, the similarity between Sensor Technologies' accelerometer and the comb drive patent would have led to litigation had an industrial company owned the patent. The relationship between the patent owner (the West Coast University) and Sensor Technologies was one of industrial partnership. Sensor Technologies had been a partner of the Advanced Institute since its foundation, and paid a membership fee for the privilege:

> [If someone asked me,] 'If you were a nasty company could you get a good lawyer and mess them [Sensor Technologies] up?'. And the answer would be if I was called in to advise a nasty company I would say, 'You wouldn't get very far. You'd get shut down'. And they might say, 'We don't care. We're going to mess them up anyway'. But since we're a university that would be really dumb.
>
> Inventor 2.

Hughes (2001, p. 562) discusses the relationship between the knowledge embodied in the Cohen-Bayer patent and the knowledge transferred during Cohen's consultancy activity with Cetus Corporation. This situation raised concern because it was difficult to isolate 'Cohen the scientist, from Cohen the inventor, from Cohen the corporate consultant' (see Section 2). The collaboration with Sensor Technologies had some commonalities, resonating with Advanced Institute Director words about how Inventor 2 '*may or may not have had a consulting as well as a research role*'. While the design knowledge embodied in Sensor Technologies' accelerators was not sufficiently similar to the knowledge embodied in the comb drive patent to pursue litigation (at least in the context of the relationship between the Advanced Institute and its industry partners), our patent citation data indeed suggest that there was necessarily some knowledge transfer related to the comb drive technology enabled by Inventor 2's collaboration with Sensor Technologies. Data show the number of citations to the focal patent in later patent applications from Sensor Technologies (Table 2). In 13% of Sensor Technologies' patents (5 out of 39), the second inventor of the focal patent is also the inventor of the Sensor Technologies patent. These self-citations can be considered proxies for the knowledge transferred related (broadly) to the comb drive technology (Alcácer and Gittelman, 2006).

5.2. Informal channels, low localization

Labour mobility from publicly funded research institutions to industry is considered a channel of knowledge transfer based on regional labour networks (Almeida and Kogut, 1999; Autant-Bernard et al., 2013). In fact, local knowledge flows based on patents decline if the focal academic leaves the region of the patent application (Azoulay et al., 2011). In the early years of the Advanced Institute, a regional MEMS industry capable of employing researchers had not been established. After being awarded a PhD degree from the Advanced Institute, White Research Laboratory (part of a big multinational firm located in the Midwest) appointed Inventor 1 as Sensor Research Manager. There, Inventor 1 went on to develop airbag applications related to the comb drive technology. This knowledge channel is considered informal since we cannot identify specific instruments used to regulate the hiring of Advanced Institute's employees by industry partners such as White Research Laboratory. It is also not localized since the company and the patenting institute were in different regions.

A firm patent inventor is another example of delocalized recruitment of human capital. Inventor D was a former West Coast University student, who finished a masters degree in MEMS at the Advanced Institute in 1997 and 'worked directly with the inventors of the focal patent'. He then moved to Oceandoor, a MEMS company in the Midwest. This suggests that even a privileged environment, such as the US West Coast, in the absence of specific industries, did not facilitate the local absorption of university researchers and graduates, which is in line with the idea that a 'critical mass' or agglomeration of firms is needed in order to obtain substantial local economic effects from spending on academic research (Varga, 2000; Hall et al., 2005).

Citations to the focal patent are indicative of the delocalization of economic impact: the distance decay typical of geographic spillovers (Jaffe et al., 1993) predicts a higher frequency of national than international citations, and a higher frequency of regional citations than national, non-regional citations. Table 3 shows that the number of international citations is less than the number of national citations: 37% versus 63% (39% vs 61% excluding self-citations). However, the second prediction is not supported: among national citations, there are more non-regional than regional ones (37% vs 18%, or 39% vs 16% excluding self-citations). Despite the predictions in the spillovers literature, the impact is lower at the local than the national level due to the absence of a critical mass of local companies (Varga, 2000; Hall et al., 2005).

5.3. Formalization and high localization

This quadrant is especially interesting in our case since it involves the most significant local impact. It includes the creation in 1997 of the West Coast University Microlab Affiliates (WMLA) programme, which allowed local entrepreneurs to experiment with the 'fabrication knowledge'[6]; related to MEMS.

> On the West Coast University campus we had the Microlab and we had a programme by which startups and companies could come and build prototypes in our lab... The West Coast Univer-

[5] By design knowledge we mean 'knowledge involved in the design of an artifice and its components, including plans, drawings, computer displays, etc.' (Vincenti, 1990, p.6).

[6] Fabrication knowledge refers to knowledge allowing design plans to be 'translated into the concrete artifice' (Vincenti, 1990, p.6).

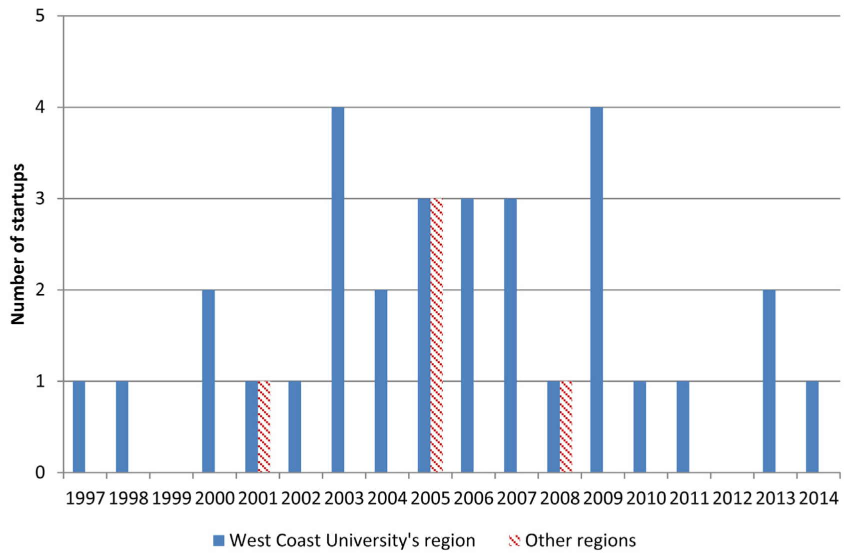

Fig. 4. Startup formations related to MEMS applications involved in Advanced Institute programs.
Source: Authors' elaboration based on web data from the Advanced Institute.

> sity was the first place that had this open access for microlabs. So, the entrepreneurs started to work over there.
>
> Advanced Institute Director.

More specifically, WMLA provided access to research space for startup companies, for a membership fee. Many of these companies were started by West Coast University graduates who requested continued access to the Microlab facilities. The number of companies varied over the years between 10 and 25 and, on average, about 20% of Microlab's income was generated by WMLA companies.

> Back in those days, not that many commercial entities actually can fabricate MEMS devices, and the Advanced Institute is one of the very few who can do MEMS devices. So, that certainly helped attract a lot of commercial interest.
>
> Inventor 1.

In turn, entrepreneurial developments that started in the Microlab, contributed to the development of a local MEMS industry, which previously was located outside the region of the West Coast University. An open lab provides a context which favours the participation of various actors (universities, research centres, firms and, more recently, customers and users) in R&D and innovation activities to coordinate tasks, facilitate knowledge transfer and share learning experiences. The underlying rationale is to break down organizational and institutional boundaries with the environment and get access to creative ideas and capabilities embodied in different stakeholders (Herzog and Leker, 2010). Open labs exemplify the opening of the innovation process in leading and pioneering industries such as MEMS (Chesbrough, 2006). The idea behind the foundation of labs like WMLA is to build decentralized research labs on university campuses to increase absorptive capacity, facilitate outside-in innovation processes and provide incubation services. These types of open lab initiatives, which allow entrepreneurial companies in high tech sectors to access university research facilities and laboratory equipment, are considered very effective for fostering a local entrepreneurial ecosystem (Hung and Chu, 2006; Mathews and Hu, 2007). The WMLA programme offered different possibilities depending on the resources of the companies:

> Companies could send an engineer, that engineer could try things in the lab, and then the engineer would go home with hands knowledge and be able to finish the job at home. The second programme that helped a lot is that many companies funded a research student in the Advanced Institute to do the work. The companies say 'well, I do not have anyone that I can spare to do this' or 'I do not have anyone who knows how to do it, so make a research contract [. . .] and the student can do [. . .] the research and share that with the company'.
>
> Advanced Institute Director.

The role of the Advanced Institute in maturing the MEMS technology can be seen in the successive creation of startups which contributed to enriching the entrepreneurial ecosystem (Fig. 4), and boosting the expansion of regional industry collaborations (Howe et al., 2003).

The development of a local MEMS industry, following the establishment of the WMLA programme in 1997, is demonstrated also by the growth in the share of West Coast University's region business MEMS patenting at the USPTO (Fig. 5).[7] Prior to 1998, the total number of patents was too low to allow computation; between 1998 and 2000, the West Coast University's region share of overall patents was null; in the decade 2001-10, West Coast University's region share of MEMS patents increased mostly annually (except in 2006–07). After 2011, we observe a gradual decline in West Coast University's region contribution to MEMS inventions (although absolute numbers of patents continued to rise).

Crucially, part of the fabrication knowledge transferred through the WMLA programme was the result of a collaboration with Sensor Technologies, which, as we have seen, from 1988 was heavily involved in MEMS consultancy with an Advanced Institute patent inventor. As mentioned in Section 5.1, during this formal collaboration MEMS designs were conceived for fabrication in both Advanced Institute and Sensor Technologies laboratories. As a side effect of this collaboration, Microlab's fabrication capabilities improved and, ultimately, were transferred to local entrepreneurs through the WMLA programme. When asked to what extent the Sensor Technologies collaboration had helped to improve the capabilities of

[7] Our version of PATSTAT does not include a technology classification for MEMS technologies; we therefore used USPTO online data, which includes this technology class in its Cooperative Patent Classification (class B81B3/0021: Micromechanical devices; transducers for transforming electrical into mechanical energy or vice versa). Hence, Fig. 5 is not directly comparable with the previous figures, which are based on PATSTAT data.

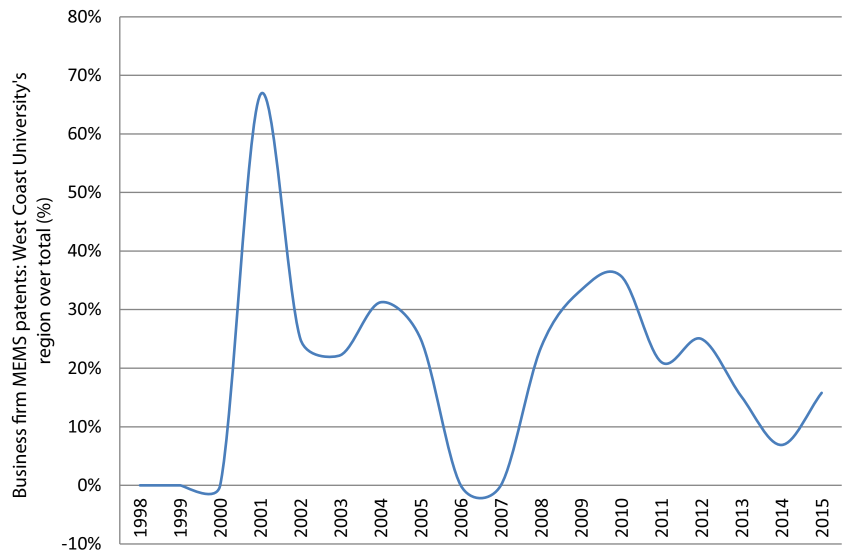

Fig. 5. MEMS patenting in the West Coast University's region.
Source: own elaboration of USPTO webpage. Applications filed at the USPTO. Only patents applied for by business firms. Manually checked geographic origin of applicants. Denominator: West Coast University's region + other US + foreign applicant patents. N = 293.

the Microlab and the impact of this improvement on the WMLA programme, the former Advanced Institute Director answered:

> Sensor Technologies put the research forward [. . .]. The most important thing was to develop a philosophy of how to design a microsensor with a better knowledge of the fabrication process [. . .]. So, we learned a lot about fabrication processes, and we learned how to tune our fabrication processes, but the Microlab was built independently [in 1983], and so the 'crossover' was primarily knowledge about fabrication process details, and not the fabrication equipment itself.
>
> Advanced Institute Director.

The fabrication knowledge transferred from industry to university during the consultancy did not involve a specific contract and did not seem to raise concerns over property rights. In fact (and perhaps paradoxically) the knowledge was transferred partly during interactions in the meetings rather than through formal contracts:

> Mostly it was a community that was exchanging information, there was no specific contract [. . .]. Advanced Institute had a contract with Sensor Technologies, but in the meetings to discuss the results of the contract, so much else could be shared and therefore everybody benefits [. . .]. For example, my sister is an artist, sometimes she works in acrylic, sometimes she works in watercolor, sometimes with other techniques [. . .]. All techniques she knows a better artist she would become. . . Sometimes the more fabrication tricks you learn, the better engineer you become, and this community was able to share all these tricks.
>
> Advanced Institute Director.

We consider this industry-university spillover concerning MEMS fabrication technology to be an informal channel. By definition, during the consultancy work, the design knowledge that was transferred from university to industry was not the same as the fabrication knowledge transferred informally from industry to the university. However, both were closely related since the formal channel of transfer was concerned with design, and the informal channel was related to the fabrication processes in Advanced Institute and Sensor Technologies facilities linked with these designs. D'Este and Patel (2007, p. 1297) highlight that 'bi-directional knowledge flow [. . .] is often neglected in the analysis of university–industry interactions; in particular, the knowledge flow from industry to university'. These authors claim that this kind of knowledge transfer can be extremely valuable for improving the capabilities of university researchers and focusing their activities on user needs. In our case, the fabrication knowledge was ultimately transferred to local entrepreneurs involved in the open lab programme.

We can now summarize our understanding of the dynamic interaction between formal and informal channels of knowledge transfer based on the case of a non-local company involved in formal consultancy work with Advanced Institute, broadly related to the comb drive patented knowledge. This collaboration resulted in the transfer of fabrication knowledge from industry to university, based on personal contacts between academic and industry researchers. In turn, it was transferred to local entrepreneurs through an open lab programme, which resulted in local economic impact. Fig. 6 shows that the Advanced Institute-Sensor Technologies relationship involved several transfer channels which were dynamically interrelated, while the Advanced Institute-MEMS Solutions (the patent licensee) relationship involved a single channel.

5.4. *Informal channels and high localization*

In addition to the informal collaboration on fabrication capabilities involving Sensor Technologies and Advanced Institute, other informal knowledge transfer channels related to the focal patent had a local impact. Our informants provided evidence that Microlab became a platform for personal exchanges between Advanced Institute academics and regional inventors in WMLA member firms. Two firm patent inventors also mentioned conferences as enabling contact with the inventors of the focal patent. One of these firm inventors was employed by a firm affiliated to Advanced Institute's industry consortium; the other worked in a non-affiliated company, which implies that the Advanced Institute had a local impact beyond West Coast University's associates.

> I knew Inventors 1 and 2 personally through contacts at academic conferences along with many of their graduate students. We were never members of Advanced Institute as it was too expensive for a small company, and we were located near West

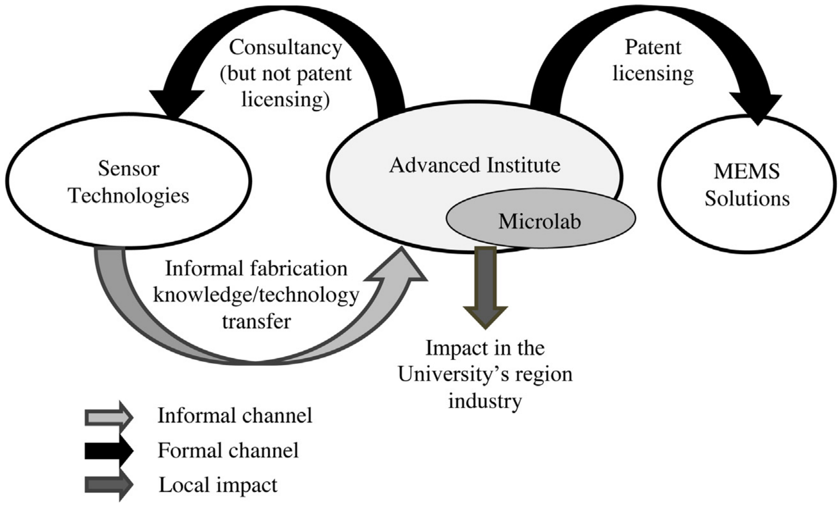

Fig. 6. Comparison of knowledge transfer channels in two cases related to the focal patent.

> Coast University and we could meet with the professors if we felt that would be useful.
>
> Inventor B.

In Section 5.2 we described how Inventor D, a former Advanced Institute PhD student, was hired by Oceandoor-Midwest while his name appears on patents filed by Oceandoor-University's region (the mother company) along with regional inventors. This suggests an intrafirm spillover via cooperation among employees located on different sites, which implies an indirect channel for local knowledge transfer: intrafirm collaboration with migrant graduates.

The above are examples of socially mediated spillovers. However, there are also direct spillovers from reading the patent or related scientific documents (such as doctoral theses and conference proceedings cited by some of the firm inventors).

> I was aware from an early date of the West Coast University's research and had seen the early technical papers.[8] However for the patent filing it is usually more expedient to reference the patents themselves rather than the technical papers.
>
> Inventor B.

The above is evidence of how informal knowledge transfer channels contributed to the establishment of a local industry around MEMS, which is in line with the literature on regional knowledge spillovers (Jaffe, 1986; Varga, 2000).

6. Conclusion

We believe our study makes several contributions. So far, the Economics of Innovation literature has remained almost silent about the dynamic interaction between formal and informal channels for knowledge transfer between university and industry. As Hughes (2001) suggests, the relationship between the knowledge transferred through various formal channels (as licensing and consulting) could be the subject of discussions on property rights. Similarly, our data suggest that the transfer of knowledge broadly related to the comb drive patent occurred through formal collaboration channels other than patent licensing. However, our evidence adds a new insight to the relationship between the knowledge transferred through formal and informal channels. During the Advanced Institute consultancy for Sensor Technologies, MEMS designs were fabricated by both Advanced Institute and Sensor Technologies facilities, which improved Advanced Institute's fabrication capabilities based on knowledge transferred via personal contacts. The relationship between the design knowledge transferred via formal consultancy activity and the fabrication knowledge transferred from industry to university (and, ultimately, to local entrepreneurs through the WMLA programme) did not seem to raise concerns over property rights, which suggests that, in these kinds of dynamic interactions, knowledge generated during formal transfer activities could be transferred via informal channels.

Our emphasis in the temporally unfolding, sequential character of knowledge transfer through different channels could encourage future work to generate systematic quantitative evidence to test propositions related with the sequence of channels. For example, through survey questionnaires or crossing citation databases with university funding databases, future studies could examine whether firms citing universities are the same as firms contracting universities, and the sequence of citations and contracts.

We also showed that local economic impact was achieved only after a complex sequence of interactions between formal and informal channels. The assumption implicit in many studies of localization is that the knowledge transferred by one channel has no relationship with the knowledge transferred via other channels. A corollary of this assumption is that the study of economic local impact can be limited to one channel. Our case study of the comb drive patent shows that local impact was achieved only after a dynamic, temporally unfolded, interaction among formal and informal knowledge transfer channels. Compared to the wider literature on local spillovers, the main difference is that, versus the typical finding of 'localization first, then delocalization' (Jaffe et al., 1993), the comb drive shows the opposite: delocalization first, then localization. Whatever comes first (local or non-local spillovers) is a matter of the absorptive capacity of the region. Hence, patent citation indicators should take into account the absorptive capacity of the territory over which knowledge spills.

Our third contribution is methodological. Until now, research on case studies of highly cited university patents had limited its attention to the Cohen-Bayer patent, which holds some similarity with our work. As in the case of the comb drive patent, Hughes (2001) study showed the concerns arose because of the relationship between the knowledge transferred through licensing and consulting. We extend and systematize Hughes' insight showing

[8] Later in the interview, the inventor clarified that he referred to reading conference proceedings.

that studies of highly cited patents could provide information not only about licensing, but also about a broad variety of knowledge transfer channels. In Section 5.4, we described how the knowledge embodied in a patent can be related to informal channels of knowledge transfer such as recruitment of researchers and recent graduates, attendance at conferences, collaboration with migrant graduates, and personal contacts between students and inventors. We also highlighted the importance of certain channels, such as consulting, personal contacts and open lab programmes, for achieving local impact.

From a theoretical point of view, this case study illustrates the limitation of current approaches to explain the complex and dynamic interactions underlying in knowledge transfer processes. Hearing the protagonists' voices enabled us to acquire a closer perspective to the micro-realm of such processes. This closer look highlighted the importance of characterizing technological knowledge as 'design' or 'production' knowledge, as proposed in Walter Vincenti's (1990) work on epistemology of technology. This typology allowed us to understand the relationship between the production knowledge informally transferred from industry to university and the design knowledge transfer involved in formal collaborations. Prior university-industry research on knowledge channels has sometimes used instead the division between tacit and codified knowledge (see Mowery and Ziedonis, 2015 for a recent example), despite its imprecision (Cowan et al., 2000). In our research we found Vincenti's approach more appropriate for analysing our data, a circumstance which could inform the design of subsequent studies (both qualitative and quantitative) on knowledge transfer.

Finally, our case contributes to the debate of the use of forward patent citations as indicators of patent value (Trajtenberg, 1990; Harhoff et al., 1999; Gambardella et al., 2008), which can have an economic or a technological interpretation (Wartburg et al., 2005; Barberá-Tomás et al., 2011). In the case of the most highly cited invention in university patenting history, the patent was licensed for less than half of the period of its protection, and its inventors perceived that its economic value in the form of royalties was low. This provides an interesting divergence with the Cohen-Bayer case, as the technological importance of the patent was accompanied by a high licensing revenue (Feldman et al., 2007). Thus, our study suggests that economic value and technological importance can diverge in the case of highly cited patents and that forward citations might not be an adequate indicator of economic value (at least in form of royalties).

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Appendix A

Table A1
MEMS evolution previous to focal patent.

Year	Event
1940s	Development of pure semiconductors (Ge and Si) and radar during World War II.
1947	Invention of the point-contact transistor and beginning of the semiconductor circuit industry.
1949	Improvement of semiconductor transistors performance (grow pure single-crystal silicon).
1959	Professor Feynman gave his famous lecture 'There is plenty of room at the bottom', describing the enormous amount of space available on the microscale: 'The entire encyclopaedia could be written on the head of a pin'.
1960	Invention of the planar batch-fabrication process, allowing the integration of multiple semiconductor devices onto a single piece of silicon (i.e., monolithic integration).
1960	Beginning of the micro-electromechanical industry.
1964	Invention of the metal–oxide–semiconductor field-effect transistor (MOSFET) and complex circuits.
1970	The resonant gate transistor was the first engineered batch-fabricated MEMS device.
1970/80	Development of the microprocessor.
1982	MEMS commercialization was started by several companies that produced parts for the automotive industry.
1983	Kurt Petersen's seminal paper titled 'Silicon as a mechanical material', increasing the awareness of the possibilities that MEMS has to offer.
1984	Feynman lecture titled 'Infinitesimal machinery'.

Source: Adapted from Judy (2001).

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