The geography of knowledge spillovers
Conceptual issues and measurement problems

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in Breschi S., Malerba F. (ed.) (2005), Clusters, Networks and Innovation. Oxford University Press. Ch. 1, forthcoming.

We would like to thank the participants to the 45° Scientific Meeting of the Italian Economic Association (SIE: 22-23/10/04, University of Bologna), Davide Castellani and Alessandra Tucci for useful comments and suggestions. Stefano Breschi gratefully acknowledges financial support from Università Bocconi and from the Italian Ministry of Education, Research and University (MIUR). Francesco Lissoni's contribution benefitted from support by the Italian Fulbright Commission and the hospitality of the Sloan School of Management at MIT. The usual disclaimers apply

1. Introduction

This paper surveys the recent empirical literature that uses mainly plant-level data and panel econometric techniques to explore the existence and spatial extent of knowledge spillovers. Following Griliches (1992) the existence of two types of knowledge spillovers is considered: pure knowledge spillovers and rent (or pecuniary) spillovers. The former are pure technological externalities, whereas the latter occur when new or improved inputs are sold, but the producers cannot fully appropriate the increased quality of their products.

Despite the analytical and policy importance of this distinction, the empirical literature has not yet been able to clearly separate these two types of knowledge spillovers. Two quite distinct traditions of econometric analysis have been trying to explore the existence of knowledge spillovers. A first group of studies has focused on the concept of localised knowledge spillovers and measured the spatial boundaries of spillovers from both private and public R&D laboratories, with a special emphasis on spillovers from universities. A second group of econometric studies has focused on international knowledge spillovers through international trade and technological transfer from the foreign branches of multinational enterprises.

We survey this econometric literature and argue that the term spillover has by now become a synonym for any kind of knowledge flow or transfer (Section 2). In particular, we point out that it is hard from these econometric studies to understand what types of knowledge spillovers affect firms' productivity and through what mechanisms knowledge spillovers are actually transmitted. This calls for a careful reconsideration of the concept of knowledge spillovers, by drawing a clear distinction between instances of pure technological externalities and market-based channels of knowledge transfer.

The fact that knowledge, as opposed to information, is inherently tacit has been used as a key argument to support the existence and the spatially bounded nature of pure technological externalities. In section 3, we provide a discussion of that assumption by arguing that, far from being an inherent property of knowledge, tacitness may actually be the result of explicit strategic choices of firms, driven by the objective to *exclude* competitors from access to strategic knowledge. Moreover, we also argue that knowledge tacitness is neither a necessary nor a sufficient condition to explain the spatial localisation of knowledge spillovers. This discussion also shows that, rather than insisting on the dichotomy tacit-codified knowledge, further progress in the direction of discriminating between pure technological externalities and pecuniary spillovers should focus on the direct measurement of knowledge flows.

The last section of the chapter addresses the empirical literature that is moving towards the measurement of the most important market-based or formal mechanisms that allow knowledge transfer and diffusion. This evidence taken together suggests that knowledge does not spill over indiscriminately and also when it leaks out it follows specific firm level, geographical and technological trajectories that might leave a paper trail. In particular we focus on the recent works that have pioneered the use of patent citations as "paper trails" left by knowledge flowing between different companies and inventors.

2. Knowledge spillovers: logical shortcomings and empirical traps

The distinction between pure knowledge spillovers and pecuniary externalities is, at least in principle, rather clear (Griliches, 1992). The former occur when firms profit from the R&D activities undertaken by others without compensating them for the benefits received. They represent *disembodied* knowledge spillovers, as they are not embodied in particular services or products but refer to the impact of ideas or compounds generated by some agent on the productivity of research efforts undertaken by others. Once a piece of knowledge is created it becomes part of the publicly available stock of knowledge, sustaining a process of endogenous knowledge creation and growth (Romer, 1990). A pecuniary or rent spillover occurs instead when a new or improved input is sold, but the producer cannot fully appropriate the increased quality of the product. In this case, some of the surplus is appropriated by the downstream producers, but this mechanism *per se* does not create further innovations and endogenous growth[1].

Although the two spillover effects can be kept distinct on a theoretical ground and despite the relevance of keeping them separate for policy purposes, when it comes to empirical studies the distinction between knowledge and pecuniary externalities becomes fuzzier. In particular, studies on R&D productivity based upon Griliches' knowledge production function may overestimate the former, and underestimate the latter, because of measurement errors (Griliches, 1992). This section is devoted to review the two main traditions of empirical literature that have adopted a *knowledge production function* approach to estimate the existence and spatial extent of knowledge spillovers. Our reading of this literature is that the distinction between the two kinds of spillovers has become gradually blurred and that in the balance between the two effects most (if not all) authors have given a special (if not exclusive) emphasis on the role of pure knowledge spillovers. The point, however, is that most of the econometric tests produced so far within the knowledge production function approach are *observationally equivalent* with respect to the role of the two kinds of externalities, i.e. they are unable to separate their respective effects.

2.1 Econometric studies on the geographical localisation of knowledge spillovers

Apart from Thompson's (1962) early effort, Jaffe (1989) is generally acknowledged as the pioneering paper in the knowledge production function approach to the geography of innovation. Aiming to assess the *real effects of academic research*, Jaffe proposes to estimate the following, modified knowledge production function:

$$\log(P_{ik}) = \beta_{1k}\log(I_{ik}) + \beta_{2k}\log(U_{ik}) + \beta_{3k}\left[\log(U_{ik})\times\log(C_{ik})\right] + e_{ik}$$

where P is the number of corporate patented inventions, I represents the private corporate expenditures on R&D, U represents the research expenditures of universities, C is a measure of within-region geographic coincidence of corporate R&D labs and university research

[1] The distinction between the two kinds of knowledge externalities is also extremely important for policy purposes. Whereas the existence of pure knowledge spillovers is an unambiguous signal of a market failure (i.e. investments in R&D lower than the socially efficient level) that calls for public support to R&D, the presence of pecuniary externalities is not necessarily associated to suboptimal market outcomes.

and *e* represents a random disturbance. The unit of observation is at the level of US states, *i*, and at the level of broad technological areas, *k*. Estimates of this model show that that the number of corporate patents is positively affected by the R&D performed by local universities, after controlling for both private R&D inputs and the state size, as measured by population. Although these results seem to support the existence of localised knowledge externalities from academic research to corporate innovative activities, Jaffe cautiously notes that "it is important to emphasize that the spillover *mechanisms* have not been modelled", by also remarking that it would be important "(…) to look more in detail at the activities of universities, moving toward an understanding of their relationship with the private sector that would really be structural" (Jaffe 1989, p. 968).

Notwithstanding these caveats, many authors have since then started replicating Jaffe's basic methodology by readily interpreting any evidence of a positive association between knowledge inputs and innovation outputs at the level of states, regions and cities as the unequivocal manifestation of *localised knowledge spillovers*, i.e. pure technological externalities bounded in space. Audretsch and Feldman (1996) and Feldman and Audretsch (1999) are two of the most representative and influential studies in this vein. Using innovation counts, from the Small Business Innovation Data Base (SBDIB), they replicate Jaffe's original methodology by showing that, even after controlling for the geographic concentration of production, innovative activities present a greater propensity to cluster spatially in those industries in which industry R&D, university research and skilled labour are important inputs. Acs, Audretsch and Feldman (1994) also find that the elasticity of innovation output with respect to university R&D is greater for small firms than for large firms, which is interpreted as evidence that small firms, while lacking internal knowledge inputs, have a comparative advantage at exploiting spillovers from university laboratories. Along similar lines, Anselin et al. (1997) refine Jaffe's original methodology to take into account cross-border effects, and show that university research has a positive impact on regional rates of innovation and that these effects extend over a range of 75 miles from the innovative region.

Although one might add further references to similar studies[2], the point we want to emphasise in this chapter is related to the proper interpretation one should give to these findings. Do these results provide unequivocal evidence supporting the importance and spatial boundedness of pure technological externalities? How much of the positive effect of local R&D inputs on innovation outputs ought to be attributed to undifferentiated and disembodied knowledge spillovers, and how much of it should instead be attributed to pecuniary externalities accruing to local firms through market-based knowledge transfer? The prevailing answer that has been given to these fundamental questions, in our reading of this literature, has almost exclusively stressed the role of disembodied, uncompensated knowledge spillovers. The theoretical foundation underlying this interpretation is, in turn, based upon the following syllogism:

a. knowledge generated within innovative firms and/or universities *spills over* to other firms, i.e. it has the characteristics of a public good, freely available to all those wishing to invest in searching for it (non-excludable) and exploitable by different users at the same time (non-rivalrous);

[2] A more comprehensive review of the econometric literature on localised knowledge spillovers can be found in Breschi and Lissoni (2001a,b).

b. knowledge that *spills over* is mainly *tacit*, i.e. highly contextual and difficult to codify, and therefore more easily transmitted through face-to-face contacts and personal relationships, which require spatial proximity;

c. knowledge spillovers are geographically localised, i.e. they represent a public good, but a *local* one, i.e. most readily available to firms located nearby the sources of knowledge.

The following quotation epitomises the premises and the conclusion of such syllogism:

> "That knowledge spills over is barely disputed. (…) Geographic proximity matters in transmitting knowledge, because as Kenneth Arrow (1962) pointed out over three decades ago, such *tacit* knowledge is *inherently* non-rival in nature, and knowledge developed for any particular application can easily spillover and have economic value in very different applications (…) The *theory* of knowledge spillovers, derived from the knowledge production function, suggests that the propensity for innovative activity to cluster spatially will be the greatest in industries where tacit knowledge plays an important role. (…) it is tacit knowledge, as opposed to information, which can only be transmitted *informally*, and typically demands direct and repeated contacts" (Audretsch 1998, p. 21-23, italics added)

Far from downplaying the importance of knowledge externalities for regional development, our claim is that this theoretical framework hides a potential contradiction, and a few traps for the empirical researchers. The contradiction is unveiled by the most recent literature on the economics of knowledge, which suggests that tacitness can be a powerful key *exclusionary* means, used to prevent other actors from fully understanding the contents of scientific and technical messages (Foray, 2004). The empirical traps derive instead from the fact that standard methodologies based on the knowledge production function at the level of states, regions and cities are hardly able to separate the effects due to disembodied spillovers from those that derive from the market exchange of rivalrous and excludable goods. Therefore, what appear to be pure externalities may turn out to be, at a more careful scrutiny, knowledge flows that are mediated by market mechanisms (Geroski, 1995).

The problem of mixing up different types of externalities emerges rather clearly in this literature when it comes to discussing the *mechanisms* through which knowledge spillovers are likely to be transmitted. Two broad mechanisms are generally identified: *social networks* and *labour mobility* (Breschi and Lissoni, 2004). Concerning the network-based mechanisms, the argument is that agents who are co-located in the same region or city are more likely to be embedded in a very thick web of social ties through which (tacit) knowledge may easily flow. The rather obvious fact that the cost of meeting personally and exchanging ideas increases with the geographical distance, coupled with the perhaps less obvious observation that the probability of establishing a social link increases with spatial (and cultural) proximity, are also often offered as key explanations for expecting thicker knowledge exchange networks among co-located agents rather than among agents who are geographically separated. Apart from observing that no evidence has been produced so far about the actual size and the density of regional networks, later on in this chapter (section 3) we argue that there is nothing on a theoretical ground to let us presume that the network of knowledge exchanges ought to include *all* agents located in a region and involved in the development of a given technology. In particular, we argue that spatial proximity is not a sufficient condition for an individual to have access through inter-personal relationships to other agents' knowledge, as long as the latter are not willing to share it and keep it proprietary. In addition, this opens up the possibility of observing the co-existence of several competing networks within the same region, rather than the existence of a single, fully connected network comprising all agents.

Regarding the role of labour mobility, and more generally spinoffs and entrepreneurship, as key mechanisms for the transmission of knowledge spillovers, the following quotation reveals once again the existence of some logical inconsistencies:

> "Why should knowledge spill over from the source of origin? (…) At least two major channels or mechanisms for knowledge spillovers have been identified in the literature. Both of these spillover mechanisms revolve around the issue of appropriability of new knowledge (…) *How can economic agents with a given endowment of new knowledge best appropriate the returns from that knowledge?* If the scientist or engineer can pursue the new idea within the organizational structure of the firm developing the knowledge and appropriate roughly the expected value of that knowledge, he or she has no reason to leave the firm. On the other hand, if he places a greater value on his ideas than does the decision-making bureaucracy of the incumbent firm, he may choose to start a new firm to appropriate the value of his knowledge" (Audretsch 1998, p. 20-21).

To the extent that knowledge is *embodied* in specific individuals and these are able to fully appropriate the value of that knowledge by founding a new firm, no spillovers take place as the knowledge is merely shifted, along with the worker, from the parent organization to the spinoff. A cluster of innovative firms may therefore emerge as a process of creation of spinoffs and new firms, without the need of invoking the existence of network-mediated knowledge spillovers as plausible explanation for it. In this respect, social networks do play a fundamental role, but for other reasons than those usually reported. The social capital of relationships with customers and providers of complementary services is essential to mobilise the necessary inputs to establish a new venture, rather than as a vehicle of knowledge spillovers (Stuart and Sorenson, 2003).

A pure knowledge spillover may still arise from the mobility of employees, but that requires two conditions: a) that the worker who transfers knowledge to another company or creates a spinoff does not compensate his/her former employee for the full inventory of ideas that travels with him/her (Geroski, 1995); b) that knowledge is not embodied in the worker that leaves the firm or that his/her separation does not imply a loss of knowledge for his/her former employer. Of these two conditions, the former is especially stringent. As suggested by some authors, it is in fact possible for employers to design labour contracts that, at least to some extent, internalise the potential externalities associated with labour mobility (Moen, 2001: Pakes and Nitzan, 1983). Therefore labour mobility may well be an important source of knowledge *diffusion*, without being a source of knowledge *spillovers*.

More generally, once we reject the idea that the evidence provided by the econometric approach based on the knowledge production function can be *exclusively* interpreted as the result of pure knowledge spillovers, the relevant questions become those of assessing the impact of knowledge transfers mediated by market exchanges and of identifying the most important market-based channels through which knowledge is diffused. As a matter of fact, a few recent papers in this tradition seem to go in the direction of suggesting that market mechanisms may explain much of the influence running from academic science to local innovation activities. Building upon his own previous work on spatial econometrics, Varga (2000) estimates the innovation elasticity with respect to academic R&D for a number of US metropolitan areas characterized by markets for business services of different size, and a different degree of specialization in high-tech industries. He finds that academic R&D expenditures impact significantly on innovation only within areas where business services and the high-tech industries have achieved a substantial critical mass. These findings may be interpreted as one more hint of the importance of markets for technologies, which need sophisticated legal and consultancy services for handling licensing, research contracts, and the financial assistance both to start-ups and large R&D projects; and of the need of thick enough labour markets for scientists and engineers for the local firms to retain new talents[3].

While Varga (2000) does not find any meaningful impact of large firms on the innovation elasticity for academic R&D, Agrawal and Cockburn (2002) do. They propose a set of cross-section regressions of the number of patents over the number of university publications in over 200 US metropolitan areas, for three science-based technological fields. After controlling for the size and specialization of the areas, they find that the patents-papers association is the strongest for those areas hosting at least one "anchor tenant", namely a large, patent-intensive firm, with some absorptive capacity in the relevant technology[4]. The authors «hesitate to draw any conclusion about a causal relationship between academic research and industrial R&D», but go on suggesting that *vertical spillovers* may exist (from universities to the local companies), which require a mediation of a large, R&D-intensive firm. One can hardly avoid to make a further speculation, and guess that the anchor tenant may indeed finance the relevant academic research, and do its best to appropriate the ensuing results: while this hypothesis leaves room for the externality hypothesis (from large firms to the rest of the local economies) it implies a market transaction between the local university and the anchor tenant.

2.2 The econometrics of international knowledge spillovers: FDIs and trade

A major contribution to the study of knowledge spillovers, and of their impact on total factor productivity, has come from research on *international* knowledge spillovers[5]. This was spurred, at the beginning of the 90s, by a wave of macroeconomic models linking technology, trade and endogenous growth. There are models with knowledge externalities and models in which knowledge is produced as any other good, and flows incorporated in new designs without producing any external effect (lab equipment models).

The models with knowledge externalities suggest that the equilibrium path of productivity growth may differ according to the extent of the diffusion of knowledge (Rivera-

[3] Varga provides a similar explanation of his findings, although one that again mixes pure spillovers (as when he suggests that local hi-tech industries allow for the appearance of "personal networks of researchers in academia and in industrial laboratories"; p. 301) with rent externalities (on the role of business services in promoting academic start-ups; p. 301).

[4] On the concept of absorptive capacity, see Cohen and Levinthal (1989). Agrawal and Cockburn (2002) consider such capacity to be in place when the company has at least one patent in the considered field.

[5] The recent literature on this issue is rather voluminous. We try to pick up the most relevant works and refer to available surveys. Cincera, Van Pottelsberghe de la Potterie (2000), Blomström and Kokko (1998) and Mohen (2001) provide extensive surveys of the empirical literature on international knowledge spillovers.

Batiz and Romer, 1991; Grossman and Helpman, 1991)[6]. For example in the model of Rivera-Batiz and Romer (1991) knowledge externalities come from the availability of a stock of knowledge that can be (re)used in research. The possibility of international flows of ideas expands the stock of knowledge that can be used in research and this has a positive impact on productivity growth. Grossman and Helpman (1991) show that if spillovers are only local in scope, each country accumulates a stock of knowledge proportional to national R&D activities. As a consequence, the international allocation of R&D resources is guided by previous experience and initial stock of technology more than human capital costs. The model equilibria display geographical agglomeration of innovative activities, as countries with even small historical advantage in technological sectors become, through higher rates of innovation, world leaders in these markets. If technological spillovers are global in scope (i.e. there is a world wide common knowledge base, which is function of the amount of differentiated products in the world economy), relative abundance of human capital generates a comparative advantage in high tech sectors because of a higher R&D performance (Grossman, Helpman, 1991; ch. 7). However less R&D intensive countries engaging in international trade can access a greater variety of inputs and grow faster than they would do otherwise.

Alternatively in the "lab equipment" models there is excludable knowledge that is transmitted through the acquisition of (a variety of) inputs (Rivera-Batiz and Romer, 1991). Importantly Rivera-Batiz and Romer point out that from the so called knowledge driven models (the ones with knowledge externalities) "one might conclude that flows of ideas are crucial to the finding that economic integration may speed up growth" (p. 548). At the same time they show that in the lab equipment model ideas *per se* have no effect on production and, moreover, extending or permitting international flows of ideas can have no economic effects.

More generally, the macroeconomic theoretical literature has shown that the possibility to re-use existing knowledge may produce increasing returns and long-run welfare effects, which depend on the geographical extension of the knowledge flows. It is worthwhile emphasising that in both Grossman and Helpmann and Rivera-Batiz and Romer knowledge driven models, endogenous growth is guided by disembodied knowledge spillovers. These knowledge driven macroeconomic models have brought the attention to the different effects on growth rates of the different mechanisms through which knowledge flows - or spills over - at the international level. These models were able to push the empirical research to enquire whether the accumulation of foreign R&D stock affects domestic productivity and to raise questions on the different channels along which ideas may be transferred.

A first generation of empirical work, in line with the macroeconomic modelling, has been performed at the aggregate level (Coe and Helpman, 1995; Keller; 1998; Eaton and Kortum; 1996, 1999). Evidence points at the existence of international knowledge spillovers but the interpretation that should be given to these results is somewhat controversial. Coe and Helpman (1995) use country level data and assume that productivity is a function of domestic and foreign R&D stocks. Foreign R&D capital stock is defined as the import-share-weighted average of the domestic R&D capital stocks of trade partners, inter-

[6] We do not survey these models here, see Grossman and Helpman (1995) and Barba Navarretti and Tarr (2000) for a link to the empirical literature. See also Eaton and Kortum (1996) for similar implications on the relationship between technology diffusion and productivity growth.

acted with the fraction of imports on GDP of the country that receives the spillovers[7]. Their (highly cited) results show that international spillovers from foreign R&D stocks affect positively domestic productivity growth and that this effect is larger for small countries. However it is not clear which is the exact channel of knowledge transmission and whether pure knowledge spillovers effectively occur. In their empirical framework, country *a* increases its productivity if country *b* increases its R&D expenditures (other things - like import shares - being equal). On the one side, knowledge might be embedded in a new - more R&D intensive - intermediate good that is imported and adopted – in this case we should talk of a rent spillover - on the other side a knowledge spillover might occur and country *a* increases its productivity using the increased knowledge stock produced by country *b*.

Keller's (1998) econometric exercise and Eaton and Kortum (1996) cast doubts on the possibility to use flows of goods to measure rent or knowledge spillovers. Keller performs a Monte-Carlo-based robustness test with randomly created trade patterns and finds positive evidence of international R&D spillovers. In a quality ladders model of innovation Eaton and Kortum (1996) show that a country's relative productivity is determined by its ability to make use of innovations. In this framework, international technological diffusion is very important because 50% of the total growth in 19 OECD countries depends upon innovations in the US, Germany and Japan and because obstacles to diffusion generate large cross-country differences in productivity. Moreover when they estimate the determinants of the number of patent applications (per worker) from country *i* for protection in country *n,* they show that this is affected by a technological diffusion parameter: the probability that an invention from country *i* is adopted in country *n*. However they find that this parameter is affected by geographical distance and years of schooling of the adopting country but that imports are not an important channel of technological diffusion.

This literature provides some evidence on the effect of international knowledge transmission on productivity growth. Evidence that trade is important as a vehicle of knowledge transmission is stronger for smaller countries accessing foreign stock of knowledge. But once again it is not clear whether trade promotes knowledge spillovers by circulating goods that can be imitated or reverse-engineered, or whether trade is just a indirect measure of knowledge transmission, once which is correlated with "real" transmission channels such as FDIs, M&A, joint ventures, user-supplier interactions, labour mobility, patenting licensing and others.

Therefore, the literature has shifted towards empirical studies that use firm level data to examine directly the microeconomic determinants of learning. However many of the logical shortcomings and empirical traps outlined above have not been resolved. In particular, in this survey we review two possible channels of spillovers: foreign direct investments (FDIs) from multinational enterprises (MNEs) and trade. We first mention, only briefly, some relevant issues in relation to spillovers through international trade. A complete analysis of this topic would extend this survey well beyond its boundaries. Then we analyse how the production function approach has been used to look for knowledge spillovers from FDIs.

In order to have a more precise grasp on the role of learning at the international level, the analysis has then shifted from the Coe-Helpman type of aggregate analysis to firm level econometric studies, which enquire whether international trade and, in particular, ex-

[7] See Lichtenberg and Van Pottelsberghe de la Potterie (2000) for a comment.

ports are conducive to higher productivity levels. It is worthwhile noting that these efforts still represent an indirect way of analysing spillovers from trade. In this respect a consensus has been reached that exporters are larger and more efficient than non exporters. At the same time these studies have failed to single out the direction of the causal nexus between export and productivity. In particular Clerides et al. (1998) and Bernard and Jensen (1998) do not find a causal nexus between export and productivity in plants in Mexico, Colombia and Morocco and in the United States respectively. Self selection seems a more plausible explanation and therefore they do not find empirical support for the learning by exporting hypothesis. This remains an highly debated issue and the empirical evidence may vary according to the specific characteristics of countries and sectors considered[8].

This controversial evidence suggests to look for different approaches and to ask different questions. In particular the most recent literature aims at measuring directly the knowledge flows and to enquire which are the precise mechanisms through firms learn about foreign technology (MacGarvie, 2003a). A promising trajectory of research uses patent citations and will be analysed in the following section of this chapter.

A more widely studied issue concerns the impact of FDIs on domestic firms' productivity and the search for knowledge spillovers from multinational corporations[9]. The most reliable results come from firm level panel data analysis[10]. The key results are: (1) knowledge is mostly transferred within firms and foreign owned firms are in general more productive, (2) spillovers to domestic firms depend upon the absorptive capacity of the host countries, (3) there is no robust statistical evidence of local spillover from FDIs, in particular for the developing countries, (4) evidence of positive spillover effects of FDIs on domestic productivity is found mostly for UK manufacturing.

The empirical work in this field uses mostly a production function approach and estimates knowledge spillovers indirectly regressing firm level total factor productivity (TFP) on a variable measuring the presence of multinational enterprises in the same industry. As an example of the methods used by this type of literature consider the influential work of Aitken, Harrison (1999) and Haskel et al. (2002).

Aitken and Harrison (1999) use a large panel of more than 10,000 plants and test whether *foreign ownership* affects the productivity of domestically owned firms in the same industry (ISIC four digit). In particular their indicator of spillover is the "foreign equity participation averaged over all plant in the sector weighted by each plant's share in sectoral employment" (p. 608). They find a significant and negative impact of this variable on the productivity of domestic firms. They control also for local spillovers arguing that the benefit from the mobility of skilled workers or from product demonstrations might be grasped

[8] Van Biesebroeck (2003) and Aw et al. (2000) find mixed evidence from Sub-Saharan Africa and Taiwan. In their analysis both self-selection and learning by exporting are an important determinants of productivity growth. In a sample of Slovenian firms De Loecker (2004) finds evidence supporting the learning by exporting hypothesis controlling for the self-selection. For a theoretical treatment of the issue see Helpman et al. (2003).

[9] There are many surveys on the empirical work on knowledge spillovers created by FDIs. (Barba Navaretti, Venables, 2004; Blomström, Kokko, 1998; Haskel, et al. 2002; Lipsey; 2001; Mohen, 2001; Branstetter, 2000; Görg and Stroble, 2001; Görg and Greeneway, 2001, 2004).

[10] Görg and Strobl (2000) in their meta-analysis of the empirical literature on MNEs and productivity spillover demonstrate that the results are affected by whether the studies use cross-sectional or panel data. Cross-sectional studies overstate the spillovers effect due to endogeneity. Moreover they show the presence of a publication bias: "studies of productivity spillovers are more likely to be published if they find statistically significant results for the presence of either positive or negative results" (p. 738).

only locally. Controlling with a variety of alternative specifications which include the foreign share of employment in a specific location, they conclude that there is no supporting evidence that technology is transferred locally to domestic firms.[11]

Haskel et al. (2002) use also a large plant-level panel in UK manufacturing in the period 1973-1992. They use two different variables to measure the spillovers: the *regional* share of total employment accounted for by foreign owned plants and, analogously, the *industry* share of employment accounted for by foreign owned plants. They use the standard 11 regions in UK and two digits UK SIC sectors. They justify the use of employment data to calculate shares claiming that "many spillover theories involve personal contacts" (p.10). Across a wide range of specifications, they find a significantly positive correlation between a domestic plant's TFP and the industry level indicator[12]. They do not find significant evidence by region.

We might wonder whether in these papers there are the appropriate sectoral aggregates and regional borders. Probably two digit SIC sectors or four digit ISIC sectors are still too broad and encompass such a wide range of specific technological fields that seem unlikely that people active in these might really catch spillovers as such from FDIs. However, since this type of econometric works use an indirect measure of knowledge spillovers, inferring their presence from their effects on local productivity, it remains impossible to know which type of spillover they are looking for. These authors in their interpretation of the results tend use the term spillover referring in particular to pecuniary or rent externalities. However we are not able to distinguish among alternative mechanisms. Therefore we do not know whether the firm level analysis for Venezuela and Morocco does not find significant results because there are no pure spillovers or rather because there is a lack of formal exchanges between MNE and local firms. The same type of question could be asked regarding the opposite evidence for firms in UK manufacturing.

Moreover in Aitken and Harrison (1999) words, "there are benefits form foreign investment, but such benefits appear to be internalized by joint ventures" (p. 617). Thus the idea is to move the analysis towards a direct estimation of the mechanism that might help transferring knowledge. Veugelers and Cassiman (2004) use the Belgian sub-sample of the Community Innovation Survey and identify the following mechanisms of technological transfer: licensing, R&D contracting, consulting advice, acquiring and selling companies and personnel mobility. They show that foreign subsidiaries acquire more technology internationally and therefore might be an important channel for technology diffusion. At the same time these subsidiaries have a lower probability of transferring know-how locally. The authors interpret this result as a higher appropriation of know-how within MNEs. MNEs might strategically minimise the knowledge spillovers, preferring FDI over licensing and/or constraining the mobility of personnel. Interestingly Veugeler and Cassiman point at the technological transfer process as a co-operative effort and "since cooperation typically involves a reciprocal relationship, one cannot ignore the simultaneity of acquiring and transferring know-how within such cooperative agreements" (p. 472).

Javorick (2004) also notes the sobering evidence on positive externalities from FDIs and claims that MNEs have incentives to prevent horizontal spillovers to local competitors and that spillovers are most likely to occur through vertical linkages. She uses a

[11] Similar results are found by Haddad and Harrison (1993) for a panel of firms in Morocco and Kathuria (2000) for India, which uses a stochastic production frontier technique.

[12] Görg and Strobl (2004) infer also the presence of technological spillovers form a life-enhancing effect on Irish plants of MNEs presence.

panel of Lithuanian firms between 1996 and 2000. The spillover variables are calculated similarly to Aitken and Harrison (1999) ones: Javorick first calculates the average (using output as weights) foreign equity participation for all sectors. These variables represent the horizontal spillovers potential. Then, she uses the input-output matrix at the two-digit NACE level to weight the average foreign equity participation in downstream sectors. She shows that the productivity of the domestic firms is positively correlated with the extent of potential contacts with multinational customer. At the same time she does not find correlation between TFP and the presence of MNEs in the same industry or the existence of multinational suppliers of intermediate inputs.

It is worthwhile noting that also Javorick (2004) infers spillovers from their impact on upstream domestic firms' TFP. These spillovers can hardly be interpreted as evidence on pure knowledge spillovers. Actually she claims that: "These spillovers may take place through (i) direct knowledge transfer from foreign customers to local suppliers; (ii) higher requirements for product quality and on-time delivery introduced by multinationals, which provide incentives to domestic suppliers to upgrade their production management or technology; and (iii) multinational entry increasing demand for intermediate products, which allows local suppliers to reap the benefits of scale economies." (p. 4). Again one can hardly avoid commenting that (i) and (ii) probably entail specific market transactions and consultancy relationship with MNEs and (iii) cannot be interpreted as a pure knowledge spillover[13].

2.3 Summing Up

As a matter of fact, within the knowledge production function literature, the term spillover has by now become a synonym for knowledge flows and transfers of any kind: licenses, labour mobility, and entrepreneurship are all mentioned as channels through which knowledge spills over. But this makes harder and harder to understand what types of knowledge flows are indeed localized, whether pure spillovers are among those, and why it should be so. Evidence also suggests that MNEs prefer internal transfer and protect their knowledge through a wide array of appropriability means including complexity, lead time, secrecy and controls over mobility of personnel. Knowledge appears as a crucial strategic asset with limited leaking out.

The review of this literature suggests that it is necessary to reconsider the concept of knowledge spillovers and to re-examine the ways in which it has been used. On one side it becomes relevant to understand under which conditions knowledge becomes an excludable good (Section 3). On the other side the empirical literature is moving towards the estimation of the most important market or formal mechanisms that allow knowledge transfer and diffusion. This evidence taken together suggests that knowledge does not spill over indiscriminately and also when it leaks out it follows specific firm level, geographical and technological trajectories that might leave a paper trail (Section 4).

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[13] Görg and Strobl (2004) show that pecuniary externalities from MNEs can affect plant start-up and post-entry performance in terms of survival and growth of firms in the host country. Alfaro and Rodriguez-Clare (2004) note that "the existence of positive externalities benefiting upstream industries should somehow have a ripple effect and benefit local firms using the same inputs as multinationals" (p. 33).

3. Tacitness reconsidered: how knowledge may flow, and yet not spill over

The notion of knowledge tacitness was first popularized in economics by heterodox students of technical change, who suggested that *technological* (and organizational) knowledge is highly contextual, hardly codified via general theories, and not fully articulated through language. Its transmission is disjoint by its use, and may be costly. As a consequence cross-firm imitation of innovations is not as easy as standard microeconomics textbook may suggest: technology is not a public good[14]. Recent extensions of the concept of tacitness to the realm of *scientific* knowledge, or science-based additions to technology, suggest that even codification and articulation through language may not be enough to eliminate tacitness.

Cowan et al. (2000) suggest that both technical and scientific knowledge are indeed often codified and articulated *via* an appropriate vocabulary. At the same time, though, the language used for exchanging technical or scientific messages is highly idiosyncratic, as it is the language of a very much close and restricted community, a so-called *epistemic community*, whose vocabulary the members learn through prolonged studies and, possibly, a few common, hands-on experiences (Steinmueller, 2000)[15]. As long as the members of the epistemic community do not disclose their common codebook (e.g. by teaching and translating it into common language, and many examples), the latter may act as a powerful exclusionary device, even for actors who live and work side by side to the epistemic community members. At the same time, since tacitness (in this new definition) and codification are mutually compatible, tacit messages can be sent even over long distance by means of a variety of communication media (both written and oral). It is up to the epistemic community members to follow some rules for retaining or selling or sharing the knowledge they master, especially when it comes to the codebook. These rules may leave to individual members who achieve a breakthrough (a scientific discovery, or a technological invention) to decide to what extent their results ought to be diffused outside the epistemic community; and what portions of knowledge ought to be freely shared, and/or sold on a for-profit basis (Dasgupta and David, 1994). Hicks (1995) describes convincingly how scientific publications may serve not the purpose of full knowledge disclosure, but that of conveying (to whatever distance) tacit messages concerning the authors' knowledge assets, in order to arise the interest of potential research partners. Similarly, the emerging literature on the markets for technologies suggests that strategic (selective) codification is essential for those markets to survive and grow (Arora et al., 2001). When it comes to university patents, licensing contracts may be extremely sophisticated in specifying what portions of scientists' knowledge should be fully disclosed, and what kept for consultancy (Thursby et al., 2004).

These observations are consistent with definitions of externalities, which see the latter as the outcome of specific institutional arrangements, rather than the consequence of some natural properties of specific goods or services. As Cornes and Sandler (1996) observe:

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[14] One classic reference on knowledge tacitness and its consequences for the theory of the firm is Nelson and Winter (1982)

[15] Steinmueller also observes that technical knowledge, far from being static, is highly dynamic. Incremental technical change takes place in all sectors of activity, and brings about new codes of communications as well as new artefacts, which change the practitioners' vocabulary incessantly: outsiders, however close, may learn nothing of it.

> "[t]he literature often treats certain types of physical goods or services as inherently possessing rivalry or non-rivalry, excludability or non-excludability. However, this can sometimes be dangerous. For one thing, the economically relevant characteristics of a good or service derive from the structure of incentives provided for its production and/or consumption. A loaf of bread typically may be thought of as a private good, but a collective enterprise that bakes loaves and distributes its output equally among it workers creates an incentive structure that is similar to that encountered in the context of public good provision. […] In many contexts there are *alternative ways of providing and distributing consumption services to individuals [with] varying degrees of excludability and […] nonrivalry*.." (Cornes ad Sandler 1996, pp.9-10, italics added).

That is, the sharing rules of the epistemic community may encompass both the extremes of pure private and pure public goods (epitomized by private consultancy as opposed to scientific divulgation), and a large number of intermediate cases between the two, such as price-excludable public goods, common property, and club goods[16].

3.1 Knowledge as a club good, and the geography of membership

An increasingly rich case-study literature on sharing arrangements within communities of scientists and engineers has emerged in the past few years (Von Hippel, 1987; Kreiner and Schultz, 1990; see also the studies quoted by Cowan and Jonard, 2000). It shows how knowledge is shared 'on request', i.e. members of the community are bound to help other members to solve well-defined technical problems, even if those other members work for rival firms. Reciprocity obligations within the epistemic community members complement the codebook disclosure rules as a powerful exclusionary device; on top of it, physical distance may, or may not, affect the ease of communicating[17]. Even when distance matters, reciprocity obligations may exclude many non-member neighbours from the knowledge flow. At the same time, such obligations may force the epistemic community members to refuse contacts outside their inner circle, and forgo their chances to access externalities generated outside it, even if at a short distance.

It is possible to object that, although physical proximity *per se* does not imply any epistemic proximity, the former may be needed to create the latter. First during the early stages

[16] Price-excludable public goods occur when the producer can sell simultaneously to many consumers, and it is possible for individual consumers to consume any amount up to the total provision, and also for different consumers to face different prices. With common property goods, access to the good itself is typically restricted to members of a certain community. In addition there are restrictions on individual members' input levels and implications for the way in which total output is to be shared among the members. For example, in the case of fishing, instead of each taking home his or her own catch, there may be a strongly established tradition whereby the day's aggregate catch is divided up equally among the fishers. Club goods generalise the public good concept to situations in which the community size is endogenous. Any additional member of the club generates benefits to fellow members by reducing the per capita cost of a given quantity of public good, but contributes to a congestion phenomenon, which in the end places bounds on the desirable size of the club. Both for local public goods share and club goods community size is endogenous, due to the existence of congestion effects. However, physical distance is the only exclusionary mechanism: all the people in the same area have access to the public good, but individuals are free to move around and finally choose the local community, or country, in which to contribute and consume public goods. All these definition summarise those provided by Cornes and Sandler (1996).

[17] For recent study on a sharing arrangement totally independent from physical distance, see Lakhani and vonHippel (2000).

of some research projects, or the pioneering of some technology, much of the relevant knowledge still has to be codified, so that it can only be transmitted by continuous interaction, practical demonstrations, and so forth. Second when frequent meetings are needed co-localisation may be a necessary requirement for belonging to an epistemic community. However, epistemic communities may well survive the end of co-localisation among their members. Even when dispersed in space, these communities will share more jargon and trust among each other than with any outsider within their present local communities. Besides, the extent and speed of the codification process will depend, once again, on economic calculus: codification costs entail some fixed costs, but help saving upon re-location and travel costs, by enabling some long-distance communications (von Hippel, 1994). As a consequence, even the length of time during which the community members will be co-located (or the time spent by a new member at close contact with some fellow ones) is not entirely dependent upon some exogenous characteristics of the knowledge base.

3.2 Markets for technology, and their geographical reach

US universities' patenting activity has greatly increased over the past 25 years (Henderson et al., 1998; Hicks et al., 2001). Although only a few patents end up earning significant licensing fees, licensing is the main mechanism through which those patents are exploited. The licensing terms may be extremely complex, and very often involve the inventors themselves as one of the licensees, or as one of the shareholders of the licensee firm. This is because most of the university patents protect early prototypes and "proofs of concept" that need much further development, which in turn call for the direct involvement of the inventors (Jensen and Thursby, 2001; Colyvas et al., 2002). In all of these cases, we may expect to observe a good deal knowledge being transferred from academic inventors to industrial researchers within companies, which we can hardly classify as a spillover. At the same time, as long as the inventor retains his position within the university, but is needed frequently inside the licensee company, those knowledge flow will remain highly bounded in space.

On a similar line, Zucker et al. (1998) argue that the notion of spillover does not apply to the biotechnology industry, at least in the phase of its emergence. While the contents of new discoveries are extensively codified, the *techniques* for their experimental replication are not. Thus new knowledge turns out to be characterized by high degrees of *excludability*: anyone wishing to build upon recently generated knowledge must gain access to the research teams and lab settings that generated that knowledge. Under these circumstances, the scientists who make key discoveries ('superstars') tend to enter into contractual arrangements with some existing firms or start up their own firm, in order to extract the supra-normal returns from the fruits of their intellectual capital. Quite naturally, when doing so, those scientists tend to prefer jobs or start-up locations within commuting distance from their home or university (where they tend to retain affiliation, also for reputation purposes and as a source of young assistants), thus creating localised effects of university research. Such localisation, however, is not the necessary consequence of any intrinsic characteristic of knowledge, but of the need to access an immobile factor of production such a star scientist[18].

Outside the realm of academic spillovers (with their problems of inventors' double affiliation), the existence of "markets for technologies" may not act as an agglomeration force, but rather the opposite. Using historical patent data for the US, Lamoreaux and Sokoloff (1997, 1999) keep track of the career patterns of a number of inventors, to relate the production of inventions to regional manufacturing activities. The main results emerging from their analysis are:

a) Although there was some clustering in both production and patenting activities, the geographic patterns were quite different. Some production centres did not have any inventive activity, while areas with very little production had very high rates of innovation.

b) Firms in clusters of production were using obsolete technologies and their location choices reflected the search for cheap material inputs. Firms using newer technologies were thus more spatially dispersed than those using older methods.

c) Patenting activity tended to be higher in regions where patenting rates *had long been high* and where a *market for technology* (as measured by the sales of patents) had evolved more fully, irrespective of the share of industry production. In regions with such well developed markets inventors tended to be more specialised, numerous and productive in terms of the number of patents per inventor.

Markets for technologies may call both for an increase of knowledge codification (patents) *and* for an increase of personal interaction between the patent holder, or the inventor, and the customers. This is the case with contracts which bundle together the provision of complementary tacit and codified knowledge, as when technical assistance and training are provided along with a license for exploiting a patent, or using a piece of (patented) machinery or software. Patents play here the ancillary role of "credible hostages" in the hands of the licensing parties, who threaten to withdraw the license if their customers try to walk away with the tacit knowledge acquired through less accountable, face-to-face contacts (Arora, 1996)[19]. In this case, codification makes the transfer of tacit knowledge feasible through enforceable contracts, and promotes both personal interaction and, if needed, co-location.

3.3 Localized labour markets for scientists and engineers

An important knowledge diffusion mechanism often cited as a case of localised knowledge spillovers is the *localised mobility* of individual (skilled) workers. As far as very advanced

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[18] Zucker et al. (1998) show that the innovative performance of biotechnology firms is positively associated with the *total* number of articles published by the local university 'star' (i.e. highly productive) scientists. However, when a distinction is made between the articles written by the star scientist in collaboration with the *firms'* scientists ('linked') and those co-authored only by other *academic* scientists ('untied'), the explanatory power of the former remains high, while that of the latter nearly vanishes. In this case we are not facing indiscriminate localised knowledge spillovers (a local public good), but tight contract arrangements linking *individual scientists* to *local firms*. For a study reaching similar conclusions outside the field of biotechnology, see Agrawal (2000).

[19] Conversely, the licensee may terminate the contract if not provided by as much assistance as needed.

knowledge is concerned (inventions, new experimental techniques, scientific novelties…) labour mobility generates pure spillovers if and only if workers moving from one firm to another help creating a common pool of knowledge from which *both the former and the new employer* are capable of drawing. That is, one needs to presume that labour mobility help spreading knowledge, instead of merely shifting it from one place to another.

Two conditions are necessary for this non-appropriation hypothesis to hold. First, some sharing-inducing incentive mechanism must be in place, which forces a firm's scientists and engineers to make a codification effort to the benefit of their colleagues or employers. Second, new employees' knowledge should not be entirely patentable and the protection of trade secrets should not be too strong.

In this respect, Fosfuri and Ronde (2004) examine how different trade secrets law regimes affect the probability that two firms will co-locate, in order to have a chance to recruit each other's engineers. For spillovers to appear along with co-location, the trade secret law must punish illicit behaviours only by awarding damages to former employers, and not by forbidding new employers to produce at all the copied goods. Fosfuri and Ronde also find that dropping the "non-appropriation" hypothesis makes their model unable to explain both the existence of spillovers and any tendency to agglomeration.

On the empirical side, a few findings by Almeida and Kogut (1999) raise doubts on the pervasiveness of labour mobility as a diffusion driver for advanced knowledge. Using a sample of semiconductors-related highly cited patents, these authors find evidence of some agglomeration of inventive activity in a few, important metropolitan areas of the US[20]. They then focus on the mobility patterns of individual inventors (engineers) within the various areas, and find them to be high and highly localised only in Silicon Valley, which also is the only area where mobility affects positively the innovation rate of local firms. In other words, labour mobility may explain localised knowledge spillovers in some cases, but not in others.

We also observe that the loss of experienced workers to the advantage of competitors can have damaging effects for those firms which are engaged in ambitious innovation projects. Those firms may either shy away from co-location or choose to co-locate only after reaching some agreements with other local companies either to limit the mobility of knowledge workers, or to reciprocate any knowledge exchange. Aharonson et al. (2004) explore these issues by studying the behaviour of entrants in the Canadian biotech industry[21].

4. Direct measurement of knowledge flows

The knowledge production function approach to the study of knowledge spillovers suggests a positive impact of academic research on local innovative activities and a mixed evidence on knowledge spillovers from trade and FDIs. As pointed out above, however, this literature has not yet been able to disentangle pure disembodied spillovers from more mar-

[20] This evidence is obtained by replicating, on a smaller scale, the experiment proposed by Jaffe et al. (1993), which we describe extensively in section 4.

[21] See also interviews to Northern Italy textile machine designers in Lissoni (2000); and Saxenian's (1994) remarks on the labour market in Route 128.

ket-mediated knowledge flows. In the previous section, we have discussed how the notion of knowledge tacitness is not sufficient to guarantee the localization of both spillovers and technology markets. We have also shown that there is a wide array of mechanisms that individuals and firms may use to make knowledge an excludable good. In addition to more theoretical work and case studies, direct measurement of knowledge flows could help clarifying these matters.

Some of the researchers who first popularized the knowledge production function approach have also contributed in this direction, by pioneering the use of patent citations as "paper trails" left by knowledge flowing between different companies, and inventors. A rough analogy is drawn with a similar use of paper citations in the scientific literature, which sociologists of science have often used to track the intellectual debts within and across various epistemic communities. Later contributions have both questioned the validity of this interpretation of patent citations, and extended their use in the direction of a neater distinction of spillovers from market-mediated diffusion channels.

4.1 Great expectations: the use of patent citations.

Patent citations can be found on the "search reports" produced by the examiners working for national and international patent offices. These reports list what is called the relevant prior art, namely any older patent or piece of scientific and technical literature which can either put in doubt the novelty of the claimed invention, or help understanding better the application contents. Some of the citations come with patent applications, and one can presume it was the inventor who added them to the invention description; others are added by the examiners, who search a number of patent and bibliographic datasets to make sure all the relevant prior art has been cited[22].

4.1.2 Patent Citations: The First Round. The geographic localisation of knowledge spillovers

The case for using citations as paper trails left from knowledge exchanges was first made by Jaffe et al. (1993; hereafter JTH). In a seminal paper aimed at finding more evidence of the localization of academic spillovers, the three considered a set of university patents, along with two samples of other patents, all of them *cited* by more recent patent documents (*citing* patents, with the exclusion of *self-citing* ones[23]). A *control* sample was also built, by matching each citing patent to a non-citing one, from the same technological class and a similar application date. By checking the inventors' address, all patents could be assigned a geographical spot, both at the national, state, and metropolitan level[24]. As long as the citing

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[22] This definition of the functions performed by patent citations holds better for the USPTO (the US patent office) than for the EPO (European patent office). On the key differences between the citation rules of the two offices, and their consequences for the analysis of knowledge flows, see Breschi and Lissoni (2004), which also provide a non-technical introduction to the relevant patent jargon.

[23] A self-citation occurs when the cited and the citing patents belong to the same company or group. A proper screening of self citations requires accurate information on each patent applicant's ownership structure at the time of the application. On the unreliability of self-citation "cleaning exercises" for large data samples, see Thompson (2003, footnote 6).

[24] Jaffe et al.'s rules on this point are quite complicated. Two full paragraphs of their article are devoted to their explanation (see page 585 of their paper).

and the control patents come from the same technology, and that to some extent the industries using that technology are concentrated in space, they should have a similar geographical distribution. However, JTH found that citing patents were much more likely to be co-located along with the cited ones, and interpreted the result as evidence of the existence of localised knowledge spillovers (however, both the academic and the non-academic patents led to the same result)[25].

Two recent qualifications of this interpretation go in the direction of telling spillovers apart from market-mediated knowledge flows, and explore separately the localization propensity of each kind of flow. Mowery and Ziedonis (2001) observe that the JTH experiment did not control for the possibility that many cited-citing patent couples hide a licensing link, as when a licensee builds upon (and cites) the licensed patent to produce an invention of his own[26]. They examine over 14,000 patents granted over many years to Columbia University, University of California, and Stanford University, for which they calculate both the number of licenses granted to companies from 50 large metropolitan areas and the number of citations coming the same areas (excluding citations from the licensees). Separate regressions of the two dependent variables over the distance between universities and metropolitan areas, plus a wide range of controls. They find that distance takes a higher toll on licenses than citations, and conclude that spillovers are less localized than knowledge flows mediated by licenses. The rationale for this conclusion is found in the work by Zucker and co-authors we discussed in section 3.2: technologies licensed by universities require much further development, and call for frequent personal contacts between the licensee and the inventors, the latter providing the necessary complementary know-how. Albeit also affected by distance, pure spillovers travel longer distances than paid-for transfer of "proof-of-concepts" and prototype inventions.

Agrawal et al. (2003) explore the role of social ties between inventors by running a modified JTH experiment, which focus on cited patents by "mobile" inventors, that is inventors who have moved at least once across different metropolitan areas (as derived from their addresses on patent documents). The units of observations are inventors rather than patents, and the co-location rates of cited-citing inventor couples are compared to the same rates for the cited-control inventor couples. The authors first confirm the JTH results and then move on to examine the matching rates between the cited inventors' early locations and the location of both the citing and the control inventors, finding again JTH-like results: knowledge generated by mobile inventors is more likely to spill over both into their current *and past* locations than anywhere else. Agrawal and his co-authors suggest that mobile inventors may have maintained some social ties with colleagues in their former locations, and that knowledge moves along those ties. As suggested in section 3.1, members of epistemic

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[25] Similar experiments on patent citations yield similar results. Maurseth and Verspagen (2002) and Verspagen and Schoenmakers (2000) conduct two studies based upon counting the number of patent citations between pairs of regions, and then estimating a model where these counts are related to the geographical distance between pairs of regions; their estimates show that the number of cross-citations significantly drop as the distance increases. See also Almeida and Kogut (1997; 1999).

[26] As a matter of fact JTH discuss this possibility (pp. 583-584, and footnote 11), but conclude that: «we expect that, in general, the contract between the two parties [from which the citations arises] will be quite incomplete, making it more likely than not that the citing organization could […] benefit from at least a partial spillover». JTH add that the co-localization bias caused by such «internalized spillovers», may be offset by the opposite bias introduced by the "noisy" citations added by patent examiners; we come back on examiners' citations in section 4.2.

communities may communicate even at some distance, once they had a first a chance to build a common understanding through co-location at an earlier point in time.

Breschi and Lissoni (2005) make an even more direct attempt to test for the importance of social ties. They mine a data set of over 30000 EPO patent applications by Italian inventors as a source of relational data, assuming that a social tie exists between two inventors as long as they are found to be listed together on at least one application. They then build the entire "social network" of inventors and calculate both the connectedness and the geodesic distance between each pair of inventors[27]. Running once again the JTH experiment, they find that the original results hold only for patents whose inventors are socially connected, and that short social distances greatly enhances the probability to observe co-location between cited and citing patents. This is taken as evidence that geographical proximity is not a sufficient condition for accessing spillovers, as long as these circulate only within tightly knitted social networks.

Thompson and Fox-Kean (2005) have criticized the original JTH paper, suggesting that the technology matching criteria followed to build the control sample may be faulty, and induce a co-location bias in favour of citing patents. The technological classes used by JTH would be too broad for ensuring that control patents mimic closely the contents of the citing ones. As a consequence, the probability for a control patent to be co-located with a cited one would be diluted by the less-than-one probability of any technology relationship with the same patent. When more accurate matching criteria are followed, the co-location premium of citing patents disappear, but for the international level. Thompson and Fox-Kean go on criticizing the whole JTH methodology, by suggesting that even a finer matching may not provide a good enough guide to matching control patents with citing ones, as the USPTO classification system is meant to ease the examiners' search procedures, but bear little relationship with the industrial activities upon which one should judge the closeness of contents between two patents. Albeit strong, this criticism may not apply to the IPC classification system, which is much more detailed and technology-oriented than the one followed by the USPTO.

The prior art cited by patent applications and search reports comprise both older patents and the so-called "non patent literature" (NPL). Scientific articles published in major peer-reviewed journals are an important part of NPL, and one to which academic scientists contribute greatly. Quite a few contributions have already exploited NPL citations to prove the growing influence of academic research on a number of science-based technologies (Branstetter, 2001b and 2003; INCENTIM, 2003). Much more remains to be done to track the geographic and social ties between the authors of the cited publications and the patent inventors.

4.1.2 Patent Citations: The Second Round. International Knowledge Spillovers

For what concerns international knowledge spillovers the point of departure is the Coe-Helpman approach that is criticised on the following grounds: i) conceptual problems estimating a production function at the aggregate country level, ii) no control for heterogeneity in terms of firms, sectors and regions, iii) no measure of technological proximity and, iv)

[27] For a definition of connectedness and geodesic distance, see Wasserman and Faust (1982).

trade is assumed as the only vehicle for spillovers (without having further subsequent support from firm level panel data econometrics). On this basis, patent citations turn out to be an extremely appealing tool to estimate also international spillovers and compare them with national and local ones.

Branstetter (2001a) uses a patent function to estimate firm level spillover effects. Based on a panel of 205 firms in five high R&D/sales ratio industries in the period 1985-1989, he provides strong evidence for intra-national knowledge spillovers and limited evidence that Japanese firms benefit from knowledge produced by American firms. As it happens with the results form micro-econometric studies surveyed in Section 2, Branstetter (2000a and 2001a) shows that - also using patent citations - the size of international knowledge spillovers could be much smaller than what regressions on aggregate data predict.

Moreover a set of recent studies using data from both the European Patent Office and the US Patent and Trademark Office cover an extensive amount of countries and analyse the geographical extension of the citing behaviour of firms. These studies do not use a knowledge production function approach but rather estimate directly how the probability to cite is affected by geography. These results seem to confirm that there are barriers to knowledge flows. Moreover an important result of this literature is that knowledge flows are technology specific and this specificity should be grasped within narrowly defined technological classes (Malerba, Montobbio, 2003; Malerba et al. 2004)[28]. Maurseth and Verspagen (2002) show that EPO patent citations occur more frequently between close regions and between regions with specific technological linkages. Peri (2003) finds that geographical distance affects more trade flows than knowledge flows. However, he finds that the probability to cite decreases with the geographical distance. In their book, Jaffe and Trajtenberg (2002) collect some of their highly influential and cited works showing that USPTO patent citations display a significant localisation of knowledge flows.

Patent citations have been also used to understand and directly test the presence of knowledge flows from FDIs. In particular Branstetter (2000b) and Singh (2004b) consider FDIs as one of the possible channels that overcome the geographic localisation of knowledge. Branstetter (2000b) analyses the impact of FDIs by 187 Japanese firms and shows that knowledge flows occur in both directions. Using USPTO patents and citations, he estimates directly the probability that Japanese firms cite the stock of patents of US firms and the probability that US firms cite the stock of US Patents of Japanese firms, controlling for an extremely wide set of factors including technological proximity. He finds that the variable measuring FDIs by Japanese firms has a significantly positive impact on both probabilities. These results are important because they are a direct estimation of the knowledge flows and because they highlight that spillovers are bi-directional.

Similarly, for a wider set of countries and firms, Singh (2004b) observes that the evidence about horizontal knowledge spillovers is controversial and puts forward the hypothesis that the flow of knowledge is bidirectional. Knowledge leaks out from FDIs and, at the same time, MNEs are able to access local knowledge stocks. He follows the match-

[28] Malerba and Montobbio (2003) show that international technological specialisation is significantly persistent and is affected by the direction of cross-sectoral knowledge spillovers within countries. Malerba et al. (2004) analyse the relative effects of national, international, sectoral and inter-sectoral spillovers on innovative activity in six large, industrialized countries (France, Germany, Italy, Japan, UK and US) over the period 1981-1995 and use patent applications at the European Patent Office to measure innovation and their citations to trace knowledge flows within and across 135 narrowly defined technological classes. They find that international spillovers are an important determinant of innovation and mostly occur within narrowly defined technological classes.

ing methodology of JTH (1993) and Thompson, Fox-Kean (2005) and compares patent citations from domestic firms to MNEs subsidiaries with patent citations from MNEs subsidiaries to domestic firms. He finds that "MNEs subsidiaries are better at gaining knowledge from domestic organisations than the latter are at gaining knowledge from the former" (p. 12).

Finally, a recent paper by MacGarvie (2003b) uses patent citations to test whether French exporters and importers receive more spillovers than matched firms not involved in international trade. She finds that there is a robust evidence the importers cite more foreign invented patents than non importers. The evidence for the exporters is weaker. For the exporters than it appears confirmed the result that association with higher efficiency is mainly due to a self selection effect. However, it seems that importers have relatively higher access to technology overseas than non importers.

The availability of large datasets of patent citations has provided a great opportunity to qualify previous results on knowledge spillovers because they are an extremely detailed source of information at the individual and technological level. This has been done in parallel with a departure from the traditional knowledge production function approach and in the direction of testing directly the determinants of the flows of knowledge (i.e. the determinants of patent citations). The main results from this buoyant stream of research are that international knowledge flows are important in particular along specific technological trajectories. At the same time there is a robust evidence that geography constitutes a significant barrier to knowledge transmission. Moreover, as shown above, the use of patent citations helps having a better understanding about the way knowledge is transferred via FDIs and trade.

While enthusiasm for these results and for the richness of the data sources is legitimate, some of the empirical traps and conceptual problems remain very open. Actually even if we can measure directly the direction of spillover and take into account sectoral and individual heterogeneity, it is still not possible to know whether these are externalities or simply a proxy for technological transfers. Moreover the more patent citations have been used, the more doubts have been raised, both by academic discussants and patent experts (such as examiners and intellectual property managers), on whether interpreting citations as inventor-to-inventor knowledge flows is both legitimate and useful. This issue is addressed in the last section.

4.2 Afterthoughts: how do patents get cited?

Exploring the intricate details of the examination procedure, and what they imply for the meaning of patent citations, go beyond the scope of this survey. A few warnings are however due. Many authors suggest that citations coming from the patent examiners, as opposed to those disclosed by applicants, cannot be interpreted as paper trails of any communication between inventors, since they were added from a third party. When included in the analysis, they may lead to overestimating the intensity of knowledge spillovers. They also lead to underestimating the importance of geographical proximity, since patent examiners pick their citations from their own patent databases, as opposed to applicants who are supposed to rely on local word-of-mouth information[29]. Moreover it has been observed

[29] This observation was originally made by JTH, and is exploited by Thompson (2003) to compare the localization of examiners' citation as opposed to applicants' citations. From 2001, in fact, USPTO data disclose

that even citations coming from the applicants may have nothing to do with word-of-mouth information: many citations do not come out from the inventors' technical reports, but are added by the applicants' lawyers in order to influence the patent examination process[30].

First, Jaffe et al. (2000a,b) indeed find that most inventors, when asked to check the patent applications concerning their own invention, admit they do not known either the patents cited and their inventors. Breschi and Lissoni (2004) however, suggest that knowledge may flow between two inventors not just directly (direct contact between the two), but also indirectly, along longer social chains or echoed by many ties within the social clique the two inventors belong to. It may well be the case that two inventors linked by a citation do not know each other, or are unaware of the intellectual debt one owes to the other, and yet some knowledge mastered by the cited inventor's has reached the citing one. In fact, Breschi and Lissoni find that the probability to observe a citation link between two patents increases with the social proximity of the inventors. Singh (2004a) finds similar results.

Alcacer and Gittelman (2004) also find that the geographical pattern of the examiners' citations does not differ widely from the pattern of the applicants' citations[31]. They also find that the examiners' citations provide more accurate information on the technologies to which each patent is most indebted (possibly because, while applicants act under the pressure of disclosing *any* information that can be useful, examiners are required to be highly selective in choosing their citations).

Patent examiners are also responsible for a higher share of self-citations at the inventor level, as if they contribute to disclose intellectual debt that the applicant would like to hide, or is unaware of. On one hand, these results suggest that the examiners do not add as much noise as feared to citations, and indeed may even correct for some deficiencies of the applicants' citations. On the other hand, they suggest that the same applicants' citations may provide a very biased account of the inventors' prior knowledge.

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the origin of each citation. Cockburn et al. (2004) also observe that patent examiners vary greatly in their ability to make assess accurately the extent of the prior art, which imply that the number and the appropriateness of the citations differ widely from patent to patent.

[30] According to the USPTO rules, applicants must disclose all the information they have at the time of filing a patent application, which may be useful to assess the novelty step ("duty of candour" rule). As a consequence, lawyers in charge of drafting the application browse a number of datasets (often with the help of technical experts who are not the same persons as the inventors) to chase for useful references. Even in the EPO system, where the "duty of candour" rule does not apply, lawyers may try to steer the examiners' attention away from some prior art threatening the novelty step of the patent, by adding a few citations pointing to another direction. In this respect, a warning flag is presented by Bacchiocchi and Montobbio (2004). They test whether the observed processes of knowledge diffusion and obsolescence reflect the specific institutional mechanism generating them. Results show that at the USPTO there are more citations per patent due to the different rules governing citation practices and that their median lag is twice as large relatively to the citations at the EPO. They also find that the relative properties of the citation frequencies in different technological fields change according to the patent office considered.

[31] In the patent jargon, especially in the US, what we call here "applicants' citations" are usually referred to as "inventors' citations". This follows the legal presumption that inventors are responsible for drafting all of the patent application. As a matter of fact, large parts of the application, especially those requiring a tedious search of the prior art, are trusted to legal experts and consultants. As such, they reflect much more the applicant company's routine procedures, than the inventors' knowledge.

5. Conclusions

This chapter has provided a critical re-assessment of the recent literature on the geography of knowledge spillovers. Knowledge spillovers may be an extremely important agglomeration force, but indirect attempts to measure them have largely abused the notion of spillover, thereby generating great conceptual confusion. What might appear, at first, as pure knowledge externalities may be either the result of market transactions, labour market externalities, or sharing agreements within epistemic communities. For each of these diffusion mechanisms to generate localized, as opposed to far-reaching, knowledge flows, different conditions have to be met. Market for technologies generate localized flows as long as the prevailing contracts combine both explicit messages and tacit ones, and the latter are as frequent as to call for the co-localization of senders and receivers; spillovers from labour mobility appear only insofar former employers may retain some of their lost employees' knowledge, and the gains to be reaped from recruiting the rival firms' employees offset the losses from losing one's own; epistemic communities may form inside specific location (as when a university or a company pioneer a new research field), but thereafter disperse and still exchange tacit messages.

The market origin of many knowledge exchanges makes it also hard to tell pure spillovers apart from rent externalities, such as those generated by thick labour markets and markets for technologies. Telling the various diffusion mechanisms apart requires direct measurement of knowledge flows. Patent citations looks like an indicator that may well serve this purpose. A number of contributions have both confirmed that citations tend to cluster in space and refined the use of citations to track both market transactions and social ties. Some evidence suggests that markets for university technologies may be more localized than pure spillovers from academic research; and that social networks of inventors, as measured by co-authorship data, may influence the likelihood of knowledge exchanges as much as geographical distance does.

Patent citations have been also used to test the presence of international knowledge spillover. Results show that international knowledge flows are important in particular along specific technological trajectories. At the same time there is a robust evidence that geography constitutes a significant barrier to knowledge transmission. Moreover the use of patent citations helps having a better understanding about the way knowledge is transferred via FDIs and trade. It seems that knowledge transfer via FDIs is bilateral or vertical to MNEs suppliers. Even if the measurement of spillovers using patent citations allow a more detailed analysis at the sectoral and individual level, it is still not possible to clearly discriminate between externalities and market mediated technological transfers. However conjectures from this survey would opt for a prevalence of the latter.

Knowledge driven models of endogenous growth have singled out knowledge externalities at national and international level as the main engine of growth. However these results cast doubt on the presence of these pure knowledge externalities and suggest that knowledge flows through market transactions and, if spillovers occur, they are of a pecuniary kind.

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