# Knowledge Spillovers, Innovation and Growth:

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*Cohen and Levinthal (1989) introduced the notion of absorptive capacity and demonstrated that knowledge spillovers can induce complementarities in R&D efforts. We show that this idea has rich implications when analyzing important aspects of the growth process such as cross-country convergence and divergence, the international coordination of climate change policies, and the role of openness in the production of ideas. We also show that the notion of absorptive capacity sets an agenda for new empirical and theoretical analyses of the role of R&D spillovers in innovation and growth.*

## 1. Introduction

In the 99th issue of this journal, Cohen and Levinthal wrote that:

‘Economists conventionally think of R&D as generating one product: new information. We suggest that R&D not only generates new information, but also enhances the firm's ability to assimilate and exploit existing information. […] we show that, contrary to the traditional result, intra-industry spillovers may encourage equilibrium industry R&D investment.’ (Cohen and Levinthal, 1989)

Traditionally, economists have thought of technology spillovers as arising from the fact that technological knowledge is a public good (Arrow, 1962). Innovation pushes the technological frontier forward and facilitates future innovation, creating externalities and a rational for the use of policy instruments such as the R&D tax credit to address this market failure. This traditional view suggests that knowledge spillovers diminish firms' incentives to invest in R&D as the returns to innovation cannot be fully appropriated. Cohen and Levinthal's critical insight is that R&D also plays an important role in learning: it increases a firm's “absorptive capacity,” its ability to assimilate knowledge from its environment. Consequently, knowledge spillovers induce complementarities in firms' R&D efforts and Cohen and Levinthal showed that knowledge spillovers may increase equilibrium R&D investment,[1] as it is only through its own R&D that a firm can exploit the knowledge created by its competitors.

This is a far reaching idea with numerous implications and applications in many research areas. The notion of absorptive capacity was particularly influential in the study of agglomeration economies (e.g. Anselin *et al.* (1997), Audretsch *et al.* (1998) and Agrawal and Cockburn (2003)), of technology diffusion (e.g. Keller (2004) and Baptista (2000)), of the determinants of firm-level productivity (e.g. Adams and Jaffe (1996) and Cockburn and Henderson (1998)), of R&D cooperation between firms (e.g. Kamien and Zang (2000) and Branstetter and Sakakibara (2002)), of the outsourcing of R&D (e.g. Veugelers (1997) and Higgins and Rodriguez (2006)), of patterns of innovation across firms (e.g. Geroski and Van Reenen (1997) and Breschi *et al*.

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[1] This increase in equilibrium R&D investment is relative to a world without knowledge spillovers. As discussed in the remainder of this paper, this observation does not mean that once absorptive capacity is taken into account there is no longer a wedge between the competitive equilibirum's solution and the social planner's solution.

(2000)) and more generally for our understanding of economic growth (e.g. Griffith *et al*. (2003) and Griffith *et al*. (2004)). Absorptive capacity is still a prominent concept, influencing frontier research.

In this paper, we focus on six issues where recent research has been particularly active and which relate directly or indirectly to Cohen and Levinthal's insights: (i) theoretical growth models where knowledge spillovers drive cross-country convergence and imply that optimal policies depend on a country's distance to the world technology frontier; (ii) models of growth and green innovation which emphasize strategic complementarities in (green) research across countries and explore their policy implications; (iii) new theoretical work examining the spillovers of R&D spending through general equilibrium effects; (iv) recent work on the role of openness in the discovery process; (v) new empirical work focusing on knowledge spillovers among individuals and offering a micro-foundation for absorptive capacity; (vi) recent empirical research on R&D spillovers.

## 2. Knowledge Spillovers, Convergence and Growth Policies

The notion of absorptive capacity plays an important role in the debate on the sources of cross-country convergence or divergence as well as in the debate on appropriate growth policies. On the one hand, knowledge spillovers between advanced and less advanced countries are a strong force underlying cross-country convergence. On the other hand, the logic of absorptive capacity points to self-reinforcing feedbacks leading to divergence: for example, the educated tend to migrate to areas with already high concentration of skilled individuals.[2] Which of these counteracting effects dominates? In this section, we discuss how the forces of convergence and the forces of divergence interact in the context of endogenous growth models.

Convergence is one of the most studied topics in the growth literature. A first approach explains convergence as a result of decreasing returns in physical or human capital accumulation. This is the neoclassical approach pioneered by Solow (1956) and subsequently developed by Mankiw-Romer-Weil (1992) and Barro-Sala-i-Martin (1991, 1995). A second approach explains convergence as resulting primarily from cross-country knowledge spillovers. Namely, innovations in one sector or one country often build on knowledge that was created by innovations in another sector or country. The process of diffusion, or technology spillover, is an important factor behind cross-country convergence. Howitt (2000) showed how this can lead to cross-country conditional convergence of growth rates in Schumpeterian growth models. Specifically, a country that starts far behind the world technology frontier can grow faster than one close to the frontier because the former country will make a larger technological advance every time one of its sectors catches up to the global frontier. In Gerschenkron's (1962) terms, countries far from the frontier enjoy an "advantage of backwardness." This advantage implies that in the long run a country with a low rate of innovation will fall behind the frontier, but will grow at the same rate as the frontier; as they fall further behind, the advantage of backwardness eventually stabilizes the gap that separates them from the frontier.

[2] More generally, Griffith, Redding and Van Reenen (2004) show empirically that R&D affects both the rate of innovation and technology transfers and, therefore, that failing to take into account R&D-based absorptive capacity results in large underestimates of the social rate of return to R&D. From a more theoretical perspective, Griffith, Redding and Van Reenen (2003) develop a model featuring absorptive capacity that reconciles a wide array of empirical evidence on R&D-based innovation and productivity convergence.

But there are also counteracting forces of divergence. Thus, as shown by Howitt and Mayer-Foulkes (2005) or by Aghion, Howitt and Mayer-Foulkes (2005), there may also be disadvantages of backwardness. In Howitt and Mayer-Foulkes (2005) the frequency of innovations in the catching-up country depends negatively upon the ratio between the distance to the technological frontier and the current stock of skilled workers: and the more backward the country, the more skilled workers are required for the country to catch up with the technological frontier. This is totally in line with Cohen and Levinthal's theory of absorptive capacity. Aghion, Howitt and Mayer-Foulkes (2005) instead explore the role of credit constraints to explain why the frequency of innovations might fall when a country falls further behind the frontier. In both cases, the combination between the advantages and disadvantages of backwardness explains not only why some countries converge while others stagnate but also why even countries with a positive long-run growth rate may diverge. This shows the role played by absorptive capacity in self-reinforcing feedback cycles that can result in either convergence or divergence.

These same considerations imply that there is a role for policies and institutions to help non-frontier countries catch up with the world technology frontier by building absorptive capacity up. These policies and institutions are distinct from those that favor frontier innovation in more advanced countries.

The idea of appropriate growth policy can be formalized in a simple discrete time model. Following Acemoglu, Aghion and Zilibotti (2006), henceforth AAZ, and more remotely Nelson and Phelps (1966), let $A_t$ denote the current average productivity in the domestic country, and $\overline{A_t}$

denote the current (world) frontier productivity. Then, think of innovation as multiplying productivity by a factor γ, and of imitation as catching-up with the frontier technology.

Then, if $\mu_n$ denotes the intensity of frontier innovation and $\mu_m$ denotes the intensity of imitation (or "technological adaptation"), we have:

$$A_{t+1} - A_t = \mu_n(\gamma - 1)A_t + \mu_m(\overline{A_t} - A_t)$$

Both $\mu_n$ and $\mu_m$ are associated with research efforts, hence this framework shares with Cohen and Levinthal the view that imitation (or "technological adaptation") is as much an investment as frontier R&D. Whether $\mu_m$ will increase or decrease with the technological gap $(\overline{A_t} - A_t)$ depends upon the relative importance of the advantage and disadvantages of backwardness.

In any case productivity growth hinges upon the country's degree of "frontierness", i.e. its "proximity" $a_t = \frac{A_t}{\overline{A_t}}$ to the world frontier, namely:

$$g_t = \frac{A_{t+1} - A_t}{A_t} = \mu_n(\gamma - 1) + \mu_m(a_t^{-1} - 1)$$

This immediately generates the prediction that *the closer to the frontier an economy is, that is, the closer to one the proximity variable $a_t$ is, the more growth is driven by "innovation-enhancing" rather than "imitation-enhancing" policies or institutions.*

While institutions or policies such as property right protection, contractual enforcement, the rule of law and macroeconomic stability are conducive to both frontier innovation and imitation, there are other institutional or policy features that tend to be more favorable to the former than to the latter.

Thus, more product market competition and more free entry encourage innovation in sectors or countries that are closer to the technological frontier, but can have detrimental effects on innovations in laggard sectors or countries (see Aghion, Bloom, Blundell, Griffith and Howitt, 2005; Aghion, Blundell, Griffith, Howitt, Prantl, 2009).

Similarly, Aghion, Boustan, Hoxby and Vandenbussche (2009) use cross-US-states panel data to look at how spending on various levels of education matter differently for growth across US states with different levels of "frontierness", as measured by their average productivity compared to frontier-state (Californian) productivity. They show that research education is always more growth-enhancing in states that are more frontier, whereas a bigger emphasis on two year colleges is more growth-enhancing in US states that are farther below the productivity frontier.[3] Moreover, in line with the feedback effect predicted by Cohen and Levinthal, they show that migration of skilled labor from less advanced to more advanced states accounts for a noticeable share (nearly 40%) of the total effect: the skilled tend to migrate to states where other skilled workers are located.

Therefore, the complementarity between absorptive capacity and external knowledge suggests that countries that are near the knowledge frontier will benefit from further advances in knowledge, while laggards with little absorptive capacity will be unable to capitalize on this new knowledge and will fall further behind. Absent appropriate growth policies restoring absorptive

[3] Vandenbussche, Aghion and Meghir (2006) obtain similar conclusions using cross-country panel data, namely that tertiary education is more positively correlated with productivity growth in countries that are closer to the world technology frontier.

capacity, e.g. in education and R&D, laggards may never be able to converge to the technology frontier, leading to a roughly bimodal distribution in the technological capabilities of countries. The role of policy is key because private investment in absorptive capacity has a self-reinforcing nature and the social returns to absorptive capacity (convergence) are not fully internalized by the private market. Thus, private market forces may fail to ensure convergence. Indeed, given the complementarity between absorptive capacity and external knowledge, at sufficiently low levels of absorptive capacity further increases in external knowledge may not increase marginal private incentives to build absorptive capacity and attempt to catch up. In addition, investment in absorptive capacity in one period may increase the marginal impact of investment in absorptive capacity in a subsequent period, as argued in Cohen and Levinthal (1994).

## 3. Knowledge Spillovers and Green Innovation

At the heart of the current environmental debate is the issue of how to organize the international coordination of policy intervention. As the benefits of reductions in CO2 emissions will be global, this sets the scene for countries engaging in classic free-riding, avoiding the costs of interventions. What if other countries are not intervening to support a switch to clean technologies? Does it still pay to intervene unilaterally? Is it good policy to make actions conditional on the level of other countries' commitments? As we will show, these issues are closely related to the broader question of the role of absorptive capacity in the diffusion of technologies.

Developing countries object to engage in costly environmental policies, as this will prevent them from catching up with more advanced countries. They object to setting mandatory targets for reductions in CO2 emissions. Why subject them now to environmental criteria which developed countries did not follow when they were in comparable stages of development?

Factoring in directed technological change brings new light on how countries should debate and negotiate on the implementation of a global environmental policy. While some of the emerging countries, like China or Brazil, are also part of the global innovation machine, most of the "South" at best can only imitate or adopt green technologies previously invented in the developed countries.

Acemoglu, Aghion, and Hemous (2013) appeal to complementarities between (green) research in developed and in less developed countries - much in the spirit of Cohen and Levinthal - to argue that by having the developed countries directing their own technical change towards clean technologies and by then facilitating the diffusion of new clean technologies, one can go a long way towards overcoming global climate change. In particular, it may not be necessary to tax dirty input production in the "South" in order to avoid a global environmental disaster: unilateral government intervention in developed countries will turn on the green "innovation" machine in the "North", which then will set in motion the green "imitation" machine in the "South" to adopt cleaner technologies developed in the "North." The higher the spillovers from the developed green innovation machine to the developing green imitation machine, the more active the "imitation" machine in the "South" to implement clean technologies rather than dirty ones. This makes a case for unilateral policy intervention by the developed countries, even if the developing countries would not take any actions. It also makes a case to ease the technology transfers from the “North” to the “South” and to improve their capacity to effectively absorb Northern technology.

Note that, quite in line with Cohen and Levinthal's theory of absorptive capacity, Southern countries need to invest in (green) innovation in order to benefit from knowledge spillovers from the North. The point is that directing innovation in the North towards green innovation will encourage Southern countries to themselves direct their R&D efforts towards green innovation.

Factoring in trade, however, introduces a more cautious stance on unilateral climate change policies. In a free trade world, if a country or region adopts unilateral environmental policies by taxing its dirty technologies, the other countries will automatically acquire a competitive advantage in producing with the dirty technology, and thus may decide to specialize in the production of dirty goods which they can subsequently export to the rest of the world. Similarly, multinational companies may decide to relocate dirty production activities and innovation to free-riding countries, and then re-export dirty goods and technologies to the region that has initiated environmental policies. This will not only create short-run environmental degradation, but will also deter or slow down the adoption of clean technologies.

In order to avoid such perverse effects of unilateral environmental policies, it is important to make clean technologies available and affordable to poor countries. Carbon tariffs (or the threat of introducing them) may come into play if and only if clean technologies are available at affordable cost, in order to prevent countries from reacting to unilateral environmental policies by specializing in large-scale production and export of dirty goods. If the threat of carbon tariffs is credible, any country or region could engage in unilateral environmental policy that could eventually be emulated by other countries and thereby solve the global environmental problem.

A particularly interesting insight of the notion of absorptive capacity in that context is that the diffusion of green technologies from the “North” to the “South” is not an entirely free lunch. In fact, less developed nations need to make a number of foundational investments in their own technological capabilities in order to subsequently be able to adopt the green technologies developed in the “North” and adapt them to their particular settings. Whether investments in green innovation in the “North” will strengthen the incentives of less developed nations sufficiently to lead them to invest in the required absorptive capacity is an open empirical question.

**4. Knowledge Spillovers and General Equilibrium Effects**

So far we have mostly focused on knowledge spillovers resulting from the law of motion of the technology frontier and their interaction with absorptive capacity. However, innovative activities in general and R&D spending in particular may have spillover effects on the rest of the economy of a different nature. Recent papers have shown the importance of general equilibrium effects that interact with the knowledge spillovers from R&D spending and result in new recommendations for R&D policy, sometimes radically different from existing policies. The role of reallocation effects and the role of the business cycle are of particular interest and are explored in greater detail below. These papers show the importance of rethinking the nature of R&D spillovers. However, they do not incorporate the notion of absorptive capacity and we believe that a fruitful area for future research would be to study the interaction between general equilibrium effects and R&D investment in models in which R&D facilitates learning in addition to creating new knowledge.

In ongoing work, Acemoglu *et al*. (2014) find that R&D subsidies may impede growth by slowing down the reallocation process from incumbents to new entrants. They make the point that R&D spillovers exist not only through the law of motion of the research frontier, but also through reallocation effects. The key dimension of reallocation in their model comes from the fact that skilled labor is used both for R&D as well as to pay the fixed cost of operating a product line. As a result, in the competitive equilibrium low productivity firms remain active too long relative to what the welfare-maximizing social planner would choose. Indeed, the social planner would take into account that by freeing resources from the fixed cost of operations for low-productivity firms, she can increase R&D. This effect is not fully internalized by the market because the skilled wage is depressed relative to its social value for the usual reasons (innovators imperfectly appropriate the returns to innovation). Structurally estimating their model by the simulated method of moments using administrative data, they find that optimal policy would combine a large tax on incumbent operations with a small incumbent R&D subsidy in order to speed up the movement of R&D resources from less efficient innovators (struggling incumbents) towards more efficient innovators (new firms). Crucially, they show that the conventional policy of R&D subsidies to incumbents results in a large welfare loss because it slows down reallocation. Introducing absorptive capacity in this model may have novel implications, as it creates another trade-off between incumbents (with a large stock of R&D and a high absorptive capacity) and new firms.

Another example of recent theory of R&D spillovers resulting in new policy recommendations is the work of Barlevy (2007). He points out the existence of a dynamic externality inherent in R&D, whose implications hadn't been fully understood so far. More specifically, he shows that the private incentives to innovate during a downturn are much lower than during a boom, because of short-run demand and productivity effects. However, the long-term social value of R\&D (through the law of motion of the research frontier) is the same regardless of whether R\&D investments take place in a boom or in a recession. As a result, the wedge between the private and social benefits of R&D varies over the business cycle. This effect, which results from dynamic knowledge spillovers, creates a rational for countercyclical R&D policy. His calibration exercise using US data suggests that introducing countercyclical R&D tax credits may result in large welfare gains. Introducing absorptive capacity in this model would presumably strengthen the results by making the wedge between the private and social benefits of R&D even more countercyclical.

**5. Openness in the Knowledge Production Process**

Green and Scotchmer (1995) were first to model early-stage research as providing a set of tools which serve as inputs to later-stage work. In their framework, increased openness discourages basic research, the reason being that there is more scope for the outcome of basic research to be "expropriated" by subsequent (or follow-on) research. However, as observed in Cohen and Levinthal (1989), a benefit of basic research is to build a firm's absorptive capacity. Therefore, by increasing the stock of publicly available knowledge, greater openness may stimulate firms' investments in basic research.

In contrast with Green and Scotchmer (1995), Aghion, Dewatripont and Stein (2008), henceforth ADS, have developed a framework in which openness can encourage basic research and in fact lead to an increase in the flow of discoveries. In ADS, research can be done either "in academia", i.e with the researcher having control rights on her research agenda; or it can be done in the private sector, with the employer determining what the research agenda should be. One advantage of academic freedom is that the researcher is ready to accept lower wages in exchange for research freedom. One drawback of academia is that the researcher may end up pursuing research which does not lead to commercializable innovations: in other words, researchers in academia may not focus on the pursuit of commercializable innovations. ADS show that it is optimal to pursue the early stages of a research line in academia, whereas the later stages require focus and therefore are best pursued in private firms. The ADS framework also sheds new light on the role of openness in the discovery process, and in particular it introduces positive feedbacks similar to those emphasized by Cohen and Levinthal.

In particular, the ADS framework points to at least two reasons for why more openness should have a positive impact on research and innovation. First, openness increases the scope for cross-fertilization among free researchers. This in turn makes it possible for an individual researcher to build on the idea that another researcher started but then decided to abandon. Thus, overall more openness improves the matching between researchers and ideas and thereby reduces the costs associated with academic freedom. Thanks to openness, free researchers can improve upon other researchers' ideas when the latter lack the expertise or desire to do so. Openness therefore increases the number of research lines that end up being pursued collectively.

Second, to the extent that academic researchers are more likely to be credit-constrained than private firms, what openness does is to reduce the academic researchers' costs of accessing new tools and ideas. Murray *et al*. (2013) explore the implications of the NIH-Dupont agreements aimed at reducing the cost of accessing information on genetically engineered mice, and they show that these agreements led to a higher flow of follow-on research, which was also more diversified.

The idea that openness should play an important role in the innovation process goes beyond the dichotomy between academic and private sector research. For example, the best-selling book *Wikinomics* shows how IBM took advantage of catering to the openness culture of Linux: this allowed IBM to obtain research input more cheaply, capitalizing on the fact that Linux contributors accept to work for free, much in the way that academic researchers accept to work for lower wages: namely because they enjoy freedom and also openness, i.e the ability to interact and exchange freely with other contributors.

Last but not least, the notion of absorptive capacity suggests that “openness” in the knowledge production process doesn't mean that knowledge becomes free for everyone to use. Individuals and institutions need to have sufficiently invested in their absorptive capacity in order to be able to assimilate and exploit “open” knowledge. Because of the role of absorptive capacity, as suggested above, knowledge in the public domain is not as much of a public good as conventionally thought.

## 6. Identifying Knowledge Spillovers From Individual-Level Data

Considering the existence of spillovers at the micro level – among inventors, scientists and researchers - is an important new area for empirical work that has the potential to provide micro-foundations for absorptive capacity by identifying the role of individuals in the process of learning. In addition, such work might reveal a number of market failures that have been neglected so far and could result in a new rational for innovation policy. For instance, inventors often work in networks that extend beyond the boundaries of the firm, such that their compensation may not fully internalize the effect they have on other inventors through knowledge creation and knowledge diffusion.

A series of recent papers have improved our understanding of knowledge spillovers in academia, for instance Azoulay *et al*. (2010), Borjas and Doran (2012) and Waldinger (2012). These papers creatively exploit various sources of quasi-experimental variation to estimate the magnitude of knowledge spillovers, but the evidence is mixed.[4] Azoulay *et al*. (2010) use the premature deaths of a number of “academic superstars” in biomedical sciences as a source of exogenous variation

[4] The absence of controls for absorptive capacity in these studies might be a factor, among others, explaning why the results are mixed. A given researcher's productivity will be less affected by this researcher's peers if he or she does not have sufficient absorptive capacity to learn from them.

in the structure of their collaborator's networks and find large spillovers. In contrast, Borjas and Doran (2012) find that the wave of immigration of Russian mathematicians to the US in the 1990s mainly had a “crowding-out effect” on American mathematicians and no positive externalities. Lastly, Waldinger (2012) finds that the expulsion of Jewish scientists from their universities in the 1930s did not result in a decline in the productivity of their peers, except for their PhD students.

These studies all rely on citations as a proxy for productivity and their conflicting results suggest that knowledge spillovers might greatly vary across fields. Further empirical work is ongoing in the profession to improve our understanding of these issues, in particular with studies focusing on inventors in private firms instead of academics and using alternative measures of productivity such as compensation in addition to patent citations. This new empirical literature raises many new questions that are currently under-researched, such as the extent to which knowledge spillovers between individuals are internalized by private firms, and whether they reflect dynamic learning between individuals, match-specific human capital or bargaining effects within the firm.

Overall, empirical work using individual-level data has a lot to tell us about the nature of knowledge spillovers and whether knowledge flows are embodied in individuals or “in the air.” Identifying the magnitude of spillovers among individuals is a great contribution to the debate on innovation policy, because the impacts of any policy may depend greatly not just on a given inventor's behavior but on a “multiplier effect” at the individual level that affects the broader innovation process. In addition, research designs based on individuals can identify knowledge spillovers from exogenous shocks affecting individuals; they are thus robust to the “reflection problem” (Manski, 1993). These new studies can thus make valuable contributions to an extensive and insightful literature on R&D spillovers across firms (see for instance Griliches (1998) and Mairesse and Mulkay (2008)).

**7. More Evidence on Positive R&D Spillovers**

Growth theory teaches us that innovation is fundamental, that it is endogenous to the economic environment and therefore open to potentially welfare-improving policy interventions. The general assumption is that there are positive externalities from knowledge and, hence, that there will be under-investment in R&D from a social point of view.

But demonstrating this empirically has proven challenging for a variety of reasons. First, if R&D decisions are endogenous, this must be dealt with econometrically by treating productivity and R&D investments as jointly determined. Second, since innovation markets will generally be imperfectly competitive there will business-stealing effects from innovation, which can lead to excessive incentives to invest in R&D from a social perspective. Third, since there is huge firm-level heterogeneity in R&D performance, a credible empirical investigation cannot rely solely on macro-economic variation as there will likely be too many confounding factors. In recent work, Bloom, Schankerman and Van Reenen (2013), henceforth BSVR, make headway on these long-standing issues by relying on US firm-level panel data over two decades covering the majority of private-sector R&D.

BSVR make several fundamental contributions to the existing literature on R&D spillovers. First, from a substantive, policy perspective they conclude that even after addressing all three of the above problems that have plagued the literature, the social returns to R&D are two to three times as large as the private returns. Second, BSVR identify the causal effects of R&D on firm performance using instrumental variables. They use idiosyncrasies of the state and federal US R&D tax credit system to develop an IV strategy. For example, they exploit the fact that firms will be differentially affected by the unexpected introduction of an R&D tax credit in (say) California, if a firm already has some R&D labs located in California prior to the introduction of the tax credit.

More specifically, BSVR set up a general model of oligopolistic competition between firms. They characterize the two offsetting effects of neighbours' R\&D on a firm's value: first, a positive effect from knowledge spillovers (i.e. your research helps me through improving my ideas); second, a negative effect through business-stealing/product-market rivalry (i.e. your ideas leapfrog my ideas). BSVR demonstrate how the two offsetting sources of spillovers can be identified in the data by considering the distance between firms in difference spaces. The technological spillover can be identified through patenting in similar fields, while the business stealing effect through overlaps in the product-market space (here the authors build on previous work by Jaffe, 1986). Using this methodology, BSVR can successfully identify both product market rivalry and technology spillover effects. And despite the importance of product market rivalry effects of R&D (the focus of many IO models of R&D), they find that the positive knowledge spillover effects dominates quantitatively.

Incorporating the channel of absorptive capacity in a model in the spirit of BSVR, which could be estimated using firm-level data, is an important area left for future research. It appears to be a fruitful research effort for at least three reasons. First, taking into account the learning channel of R&D should increase the social rate of return to R&D relative to the estimate of BSVR and it would be instructive to compare estimates from firm-level data with existing cross-country estimates of the learning effects of R&D. Second, the learning component of the social rate of return to R&D may vary considerably by firm size: for instance, a marginal increase in R&D may have larger learning effects in small firms compared to large firm (this effect would counterbalance the finding of BSVR, who show that the positive knowledge spillover effect of R&D is smaller in small firms, compared with large firms, because they tend to operate in technological niches, suggesting that the R&D tax credit should be increasing with firm size).
Third, comparing the results of such a study with the results of the ongoing studies based on individual-level data described in the previous section would give us a better sense of the relative importance of organizational-level versus individual-level determinants of absorptive capacity.

## 8. Conclusion

Cohen and Levinthal pointed out that knowledge spillovers have implications that go beyond the familiar free-rider problem in R&D spending. They introduced the notion of absorptive capacity and showed that knowledge spillovers can induce complementarities in R&D efforts. Here, we showed that this idea has rich implications when analyzing important aspects of the growth process such as cross-country (or cross-state) convergence and divergence, the international coordination of climate change policies, or, at a more basic level, the role of openness in the production of ideas.

At the same time, Cohen and Levinthal's notion of absorptive capacity set an agenda for new empirical and theoretical analyses of the role of R&D spillovers in innovation and growth. Here, we mentioned recent studies on reallocation effects and the dynamic aspect of R&D spillovers and recent attempts at estimating the magnitude and nature of knowledge spillovers and learning effects from individual-level and firm-level data.

Taken together, these theoretical and empirical studies should help improve our understanding of the innovation process and of the appropriate policies and institutions to enhance sustainable growth.

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