Documents de travail

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Document de Travail n° 2022 – 12

Avril 2022

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Research management models to promote breakthrough innovation: analyzing success case stories of simultaneous discovery-invention research processes

Jean-Alain Héraud [1], Nathalie Popiolek [2]

Abstract

Economic innovations are not systematically triggered by scientific discoveries or technological inventions. They can benefit from a new scientific idea without really depending on it as a key element. For instance, incremental innovations almost by definition do not exploit a new techno-scientific paradigm. Moreover, some very creative ideas happen to arise in other fields than science or technology, like the domain of usage. Nevertheless, scientific discoveries and breakthrough innovations, during the 20th and 21th centuries, were often linked. We wish to check here the existence of cross-fertilization mechanisms between academic and industrial researches in specific cases of high creativity level, and try to describe the simultaneous discovery-innovation process taking place at such occasions. We base our study on historical examples and a series of interviews of actors from public research organizations as well as industrial R&D departments. We learnt a lot about the various dimensions of the knowledge co-creation, but also about the difficulties to overcome in such cooperative schemes: differences in individual and institutional motivations, in the perception of science (its *raison d'être*, its ownership), of risk, and of time (unsynchronized clocks).

Keywords: Academy - industry partnerships, Discovery, Models of innovation, Radical innovation

***JEL* codes:** O31, O32

Introduction

The Covid-19 pandemic has just increased and reoriented certain aspects of the necessary adjustment of our socio-economic system in response to such challenges as climate change, loss of biodiversity or digital transformation. In the transition phase to the "next world", research is expected to play a crucial role in many fields like health, environment, energy, transportation, agriculture, etc. Most of the developed countries are considering how to design their research agenda. To give an example of the multiple ways science can help to tackle very concrete issues, thanks to adequate generalized vaccination we could get out of the sacrificial dilemma of "social distancing" versus propagating the pandemic. In the case of the global growth dilemma: research is hoped to bring solutions for the protection of the planet without departing from our usual social contract where consumption always increases in the long run. Implicitly or explicitly all governments count on science to find solutions to such almost impossible challenges. Creativity is the way to escape problems for which we cannot find relevant solutions given the state of the art of existing knowledge,

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but the difficulty for policy makers is that science cannot really be an object of planification. No more than the flow of discoveries produced by basic research, the mechanism of firms' innovation is not a simple linear deterministic process. The best that managing organizations can do is to give the means and good general conditions for research to develop interesting opportunities of discoveries and innovation (and, at intermediate level, technical inventions).

The relationships between science and innovation are complex and evolutive (Héraud, 2017). Innovation studies as well as science studies have showed the complex knowledge translation chains occurring in the process of ideation prior to the stage of discovery, invention or innovation. The role of scientific knowledge in the innovation process is an evidence nowadays, but at the same time scientists can no longer be considered as having the monopoly of the discovery: we observe a democratization of the ideas, as Edmund Phelps (2013) says.

Our aim here is to address the question of enhanced creativity when discoveries and innovations are pursued within the same process. The specialized literature on science-industry relationships (*eg* Etzkovitz & Leydesdorff, 2000; Rothaermel et al, 2007) and collaborative research management (Meyer-Krahmer & Schmoch, 1998; Carayol, 2003; Tijssen, 2018) tends to distinguish different contexts linked to research orientations. The latter consideration is related to specific theoretical constructs we want to remind here. The historical vision opposes the "science-pushed" model (Schumpeter) to the "market-pulled" model (Schmookler). Another seminal contribution, that of Kline & Rosenberg (1986), tries to import more complexity into the scheme with a series of feedback loops, but still builds on a market-pulled model and, in our opinion, fails to reveal all the complexity of the creative process, especially in the case of great breakthroughs. The point we raise here is one limitation of these intellectual constructs: in all models the scientific and industrial research processes are considered as distinct. They influence each other but have their own protocol. We start from the hypothesis that a joint R&D project is also possible between two entities pursuing different goals – but anticipating concrete returns in each field.

As Godin (2006) pointed out, the reference framework for the management of R&D in the decades after WW2 was clearly very linear, leaving therefore few spaces for the description of intimate interactions between actors of basic and applied research. Let us add that the use of these general models was often macroeconomic in the literature; therefore, the implicit assumption was a sort of global division of labour: "public institutions and basic research" *vs* "private actors and applied research". As we hope to show with some examples of important Science and Technology (S&T) successes, the reality does not fit with this typology. The distinction exists between the purpose of research – the beauty of science and publications on the one hand, and applications and innovations on the other hand – but this does not necessarily correspond to the typology of public and private research.

1. Models of innovation

The first linear model is, supposedly, a translation of the thought of Schumpeter, expressing a strong scientific determinism – as if only science and basic research were sources of creativity in the economy. This is maybe the intellectual bias of the first publication Schumpeter (1911), but certainly not of the whole work of the "founder" of the economics of innovation. For instance, Schumpeter (1947) expresses the fundamental creative interaction of the innovator/entrepreneur with the economy as a whole. The initial success of the science-pushed model is probably also linked to the famous Vanevar Bush report in 1945, explaining that science can become the "new frontier" of the US (and the rest of the world) after the war. Developing big science projects with the help of public laboratories as well as universities was central in the policies of this period, and, within such a strategy, basic research was definitely part of the game of economic and social development. The corresponding intellectual model is given in Figure 1. It postulates that scientific research always leads to interesting results that could help mankind after a series of translation activities called applied research, industrial development, prototyping, diffusion, copying, etc.

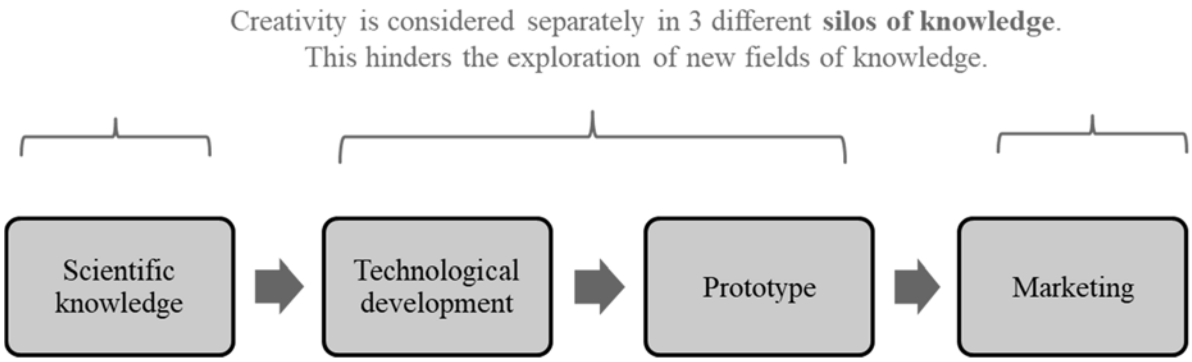

Figure 1: The science-pushed linear model of innovation

The public policy approach associated with this model involves a significant financing of basic research. The researchers are free to choose and manage their research agendas. It is also relevant here to mention the von Humboldt University model – still very present in the German system since it is written in the constitution. The results are peer-evaluated and in case of success of the process of evaluation these "discoveries" are freely available for mankind. The motivations of the researchers are mainly "the beauty of science" and their individual career in the scientific institution.

Schmookler (1966) was the first author to underline the prevalence – across the history of industrial firms – of another innovative scheme a linear model starting from the market needs. It is presented in Figure 2. Since the actor considered here has a precise innovation in mind, its objective is not the creation of knowledge in itself; and the straightforward strategy for him/her is to adapt existing cognitive assets (applying science as it is, using equipment and competences at hand...). The creative dimension exists but is limited to these adaptive mechanisms. Advances in basic science are not part of the plan.

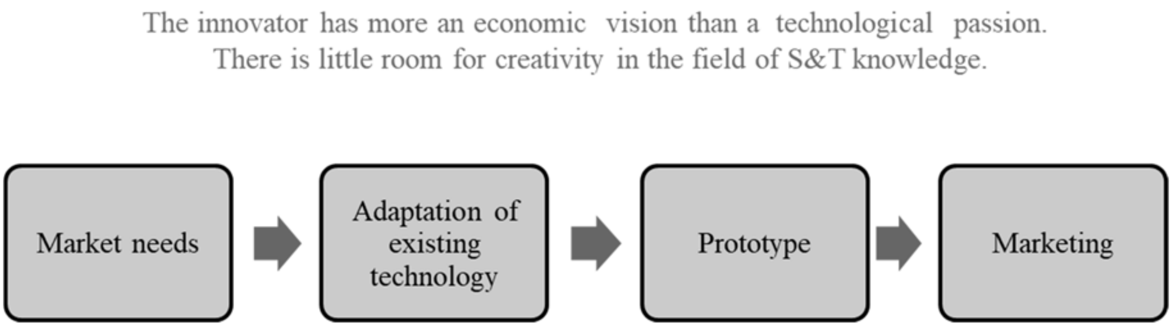

Figure 2: The market-pulled linear model of innovation

The public policy in line with this vision is to help firms accessing the right knowledge, reducing the risk and/or the cost of the development, and many other incentive actions. Of course, the role of the State is also to fund basic science, but the policy of science is conceived as separated from that of innovation.

Both linear models can be criticized as not relevant in the case of disruptive innovation. The second because it only explains step by step improvements, the first because the emergence of great new knowledge or ideas is not explained by the economy (science falls from the sky).

In terms of policies the category which is inspired by the science-pushed vision has a priori a weakness if we consider that, to a large extent, innovation is private sector's job. The only way to support firms is to embark them into big programs massively subsidized by the government and associating all actors – including basic science institutions. It has been done with the US nuclear program, the Apollo program of the NASA, etc. In France we can refer to the Diamant rocket, Concorde or TGV. Policies influenced by the second model cannot be so ambitious. Governmental action should limit itself to supply good general conditions for the firms, in terms of public infrastructures, education, diffusion of information and knowledge... The German transversal policy developed in the eighties is a good example of that sort of policy. The tax-credit system (extremely developed in France nowadays) is a neutral support that also fits into this vision of helping/rewarding firms to engage into their own innovative strategy.

The first attempt to give a theoretical representation more conform to the complex systemic reality of the innovation process is the non-linear "chain linked" model proposed by Kline & Rosenberg (1986). It underlines the multiple feedback loops between the different stages of the process going from the first idea to the complete realization as seen on Figure 3.

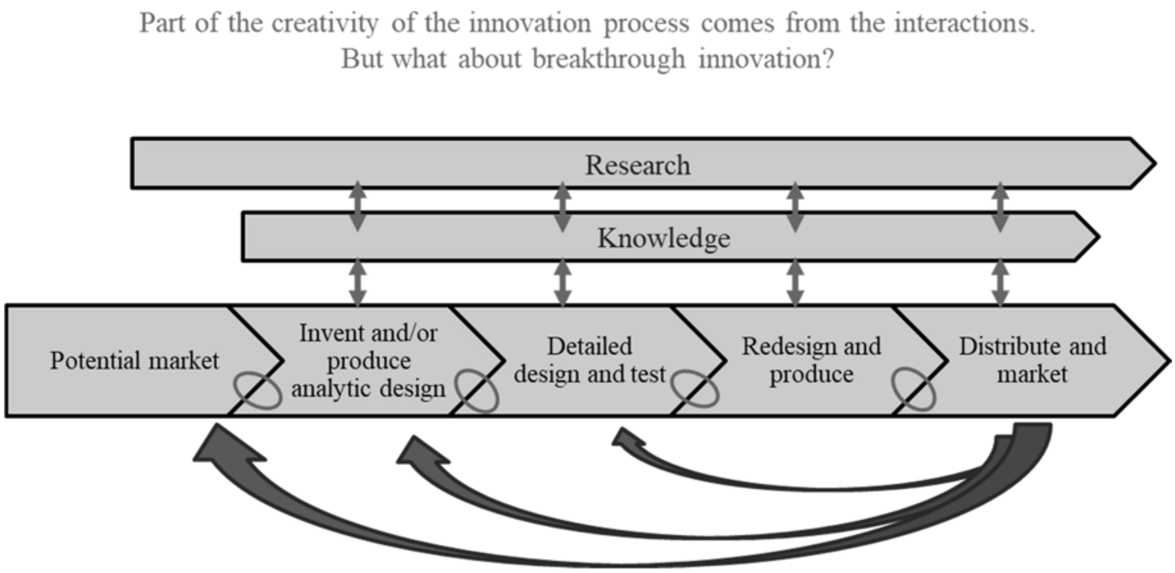

Figure 3: The chain-linked model of knowledge creation and innovation

The horizontal sequence at the bottom of the global scheme exhibits more or less the same elements as the demand-pulled linear model: the story starts at left with a first idea of some product/process responding to a potential market, but the development of the idea (in the righthand direction) constantly adds new bits of knowledge and complementary ideas. Feedback loops develop everywhere, from engineering observations inside the development or prototyping phases to remarks of the first users. The result can be just a correction of the project or a more complete redesign.

Concerning the science-pushed mechanisms, which are represented in the vertical dimension, we see that scientific research is partly responsible for the new ideas incorporated in the innovation process, but not in a linear top-down way, since basic research appears to be stimulated by the questions raised during the whole process of innovation conception. In fact, like in the Schmookler vision, if the existing stock of knowledge is enough to respond the questions raised along the conception/development phase, research is not necessary, but in certain cases, the questions meet no straight-forward responses in the textbooks, scientific articles, expert knowledge, databases, etc., and stimulate new knowledge creation (research). Kline and Rosenberg underline in their figure the importance of non-autonomous basic research leading to many discoveries. The socio-economic system is interfering with the research agendas, even in the domains of basic science. Creative loops arise in the vertical dimension as well as in the horizontal dimension.

In this paper, we want to go a little further in the direction of understanding the concrete modalities of articulation between pure research activities and innovation development mechanisms. Particularly in the case of disruptive innovation, applied researchers quickly face the limits of using established scientific knowledge and need more exploratory activities (Roussel, *at al.* 1991) – often in collaboration with public researchers. Building on Stokes (1997), Goldstein and Narayanamurti (2018) describe a *simultaneous discovery-invention* research scheme which is based on the scientists' commitment to addressing basic research questions through applied research. For instance, the model of SDI research was effective in the US Department of Energy. Other authors extended these observations to a broader range of university-industry projects (*e.g.* Plantec, Cabanes *et al.* 2021).

2. Our research questions

We would like to test the idea that researchers' creativity increases when they participate in *simultaneous discovery-invention* (SDI) research projects. History gives many examples of Nobel laureates (beyond the well-known cases of IBM and Bell Labs) benefitting from their engagement with the industry for their breakthrough discovery. An econometric study showed that one-fifth of the studied Nobel cohort was engaged with the industry at the date of the major discovery. And in the 2010-2016 period more than 50% of the laureates were inspired by the industry for their achievement (Plantec, Le Masson et al., 2021). In the next sections we will give precise examples from the literature as well as from a series of interviews we have done.

Our basic assumption is a research field clearly composed of two different sub-fields, *basic* (mainly academic) and *applied* (private and public) research, that have independent rationales and agendas, but very often reinforce each other. Figure 4 below present this conception with a Yin-Yang looking design in order to underline the reciprocity of the relationship: in each category of research there are some elements of the other that strongly contribute, and there is no hierarchy between them, *i.e.* the global model is not linear/causal, and progress goes in parallel.

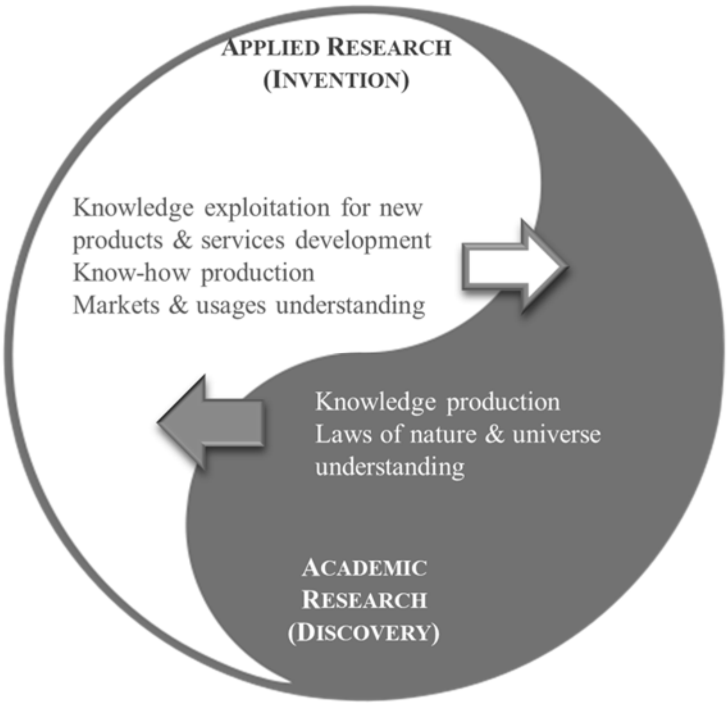

Figure 4: The cross-fertilization between academic and applied (industrial) research: synergies to explore new fields of knowledge

Hadamar (1945), who studied the psychology of the creation in scientific domains like mathematics, showed that the reasoning of the scientist is similar to an *exploration of the unknown*. Hatchuel *et al.* (2013) and Le Masson *et al*. (2017) confirm this observation in a variety of situations, in the design of production and services as well as in the design of scientific results. Our research topic is how the common exploration of the unknown is achieved through collectively working between public research organizations and industrial organizations: the unknowns of science are articulated on the unknowns of the demand (and more generally of the desires of the society) in terms of products, services and usages.

As proved in the case of semiconductors (Le Masson *et al.* 2012) common creativity can be characterized as a process through which researchers with different profiles working on the same research and innovation project manage to remove the biases and cognitive fixations that exist both in the academic community and in the industry. On the academic side, maximising the output of publications may produce fixing effects, leading them to a reduction in the quality of exploration (Le Masson, 2020), but the search for a compromise between the objectives of peer-reviewed publications and industrial valorizations help to overcome such a bias of the academic institution. On the other side, with the help of the scientists, the industry can escape *the risk of sacrificing exploration to exploitation* – in the balance of organizational learning introduced by James March (1991).

With the help of some interviews (and reading the literature), we would like to understand to which extent academic researchers are able to ask new questions and test new hypotheses when they participate to common projects with industry; and as for the applied researchers from the industry, to which extent they develop new skills and promote breakthrough innovations and other novelties that are desirable for the society. Why does collaboration help all the actors to succeed on their respective agendas?

3. Our methodology

We interviewed researchers from Public research organizations (PROs) and industrial laboratories to highlight through specific examples how both are able together to increase the level of creativity in a specific field of knowledge and economic activity. The interviews were carried out as part of a CEA (*Commissariat à l'énergie atomique et aux énergies alternatives*) project which took place during the period September 2019 to March 2020. Following these interviews, two round tables were organized during a feedback seminar (Archambault, Popiolek, 2020). The first one, led by Pascal Le Masson (2020), focused on partnership models favoring the double impact (scientific and socio-economic), and the second one, led by Pierre Bitard (2020), analyzed in a more institutional way how to promote the relationship between science and industry in a research and innovation ecosystem. As already mentioned, we will focus on the partnership model between researchers in public and private laboratories to shed light on how they are challenging each other with interesting questions for their research. So, we will not focus on organizational aspects at the institutional level but rather at the project level to analyze the reasoning of researchers in an unknown environment. The active agent here is not an institutional but a specific knowing community composed of researchers associated in a project (Amin & Cohendet, 2004).

The institutional sample was made up of three types of actors depending on whether they are belonging to public research, industry, or another organization in the research and innovation ecosystem:

- PROs: CEA (the French agency for nuclear and alternative energies), BRGM (French geological survey), CNRS (French national center for scientific research), IFPEN (Oil and new energies), INSERM (French medical research institute), Paris-Saclay University;

- industrial R&D departments: Atos, Decathlon, TotalEnergies, Microsoft France, Thales;

- associations linking public and private research: French Hub for digital & ecological transformation (Cap Digital), National association for research and technology (ANRT).

We asked the interviewees to describe one or more successful experiences in which they benefited from a fruitful working relationship with researchers outside their community. They had to explain how this relationship had been leading to an innovative path and had been helping them to innovate, sometimes in a radical way. We also wanted to know how these researchers had planned or even promoted such meetings – we assume indeed that these were not random results. Although the interviewees were only French, the examples could relate to R&D projects or experiences lived abroad.

4. The results

Our case studies, by definition, cover both the academic world which is aiming to a large extent at contributing to basic science, and the industry which is expecting new and relevant knowledge for potential innovation. For the sake of clarity, we will consider sequentially the academic researcher's point of view (4.1) and the industrial point of view (4.2), although we advocate the model of co-creation in the fields of science and technology for each radical advance. In fact, the entry point is the type of interviewee we mention.

4.1 The academic researchers' experience

a) Let us start with a major discovery/invention described by Albert Fert, the 2007 Nobel laureate in physics (the prize being shared with Peter Grünberg). The interview was conducted in the offices of Thales by Pascal Le Masson and Nathalie Popiolek[3]. The discovery is the Giant magnetoresistance (GMR) and the associated innovation is a radical change in the hard disk technology through the development of a new type of electronics called *spintronics*. Albert Fert explains that the GMR discovery was the result of a collaboration between his team at Solid Physics Laboratory of the Partis-Sud university and that of Alain Friederich at Central research laboratory of Thomson CSF company (now Thales). The industrial lab was developing *molecular beam epitaxy*, a new technology allowing the deposit of ultra-thin layers on semiconductor materials. This technology greatly interested Albert Fert who could imagine it as a new way of studying magnetic multilayers. Therefore, the academic discovery came from merging ideas in fundamental physics and new technological knowledge, thanks to a discussion between actors of the two sides (academic and industrial). Before this crucial meeting, the scientist was already looking for an industrial lab that could help him in the experimentation of his scientific project. The opportunity to meet the R&D engineer Friederich came in a very natural way since he was a former doctoral student of Fert. Furthermore, the engineer had kept a pronounced taste for theoretical physics.

This example of cooperation between university and industry shows how a sophisticated technology gives the possibility to test hypotheses in the field of physics, generating a strong scientific impact and simultaneously a socio-economic impact through a major innovation in the electronic industry. The sociological aspect of the story lays in the possibility given by two individuals to bridge two different communities (academic and industrial) in the definition of coordinated research agendas. In this sense, Fert and Friederich played the role of *knowledge brokers* or *boundary spanners* (Cohendet, Héraud & Llerena, 2013) for the co-construction of competences and knowledge.

b) An interview at CEA confirms the role of the instrumentation in the co-development of basic and applied knowledge. Instrumentation is essential for *big science* – typically particles accelerators. In this domain, as compared with the *research-pushed* theoretical model, the customer-supplier relationship is even reversed: it is not the public research institutions in basic science that offer ideas of innovation to the industry, but the industrial labs that sell innovative instruments to the big science. Researchers in pure science express their needs for state-of-the-art instruments to the specialized firms, and via the specifications they formulate, they induce innovations in cutting-edge technologies. Such cognitive interactions take the form of a sort of dialogue where researchers' dream is faced to achievable innovation. CEA researchers mention several projects illustrating this scheme, not only in high energy physics, but also in astronomy, space, defense, etc. The agile co-construction approach allows scientists and engineers to overcome their constraints and open the door to significant innovations which will subsequently spread in the consumer industry.

Medical research and biology have also recently given good examples of co-construction, with the race for vaccines against corona viruses. Basic science and applications developed in parallel and the role of heavy equipment appears here also crucial, since nothing could have been done without cryogenic electron microscopy. To be precise, the issue was not only around the existence of firms

[3] A more complete description of the case is given in Archambault & Popiolek (2020).

able to produce and sell instrumentation, but about the whole system around the equipment: the only way to be present in the race for Messenger ribonucleic acid (mRNA) vaccines is to have a cryo-microscope, plus an experienced team of scientists and technicians for operating and using it.

c) The case of BRGM, which is a public research organism specialized in earth and environmental sciences, shows the difference of epistemic context between sciences. The interfaces science/innovation are as important as in physics, for example, but of another nature. A major research orientation of BRGM presently is the application of big data techniques to various aspects of the exploration of the geological subsoil, like geothermal energy, carbon capture and storage, or waste water management. Our interviewee explained that geology is a descriptive science, modelling geological objects, to the difference of physics which is mainly reasoning with laws in a deductive way. Here, analogical thinking is more important than deductive thinking. For instance, geological situations are observed during oil or mining exploration and researchers compare these observations with known and well-characterized deposits or other subsoil objects. In such a research context, the collaboration with oil companies (*e.g.* TotalEnergies) is crucial because firms bring observations that scientific institutions would not otherwise have access to. Industry, in this case is similar to a large experimental facility. The collaboration gives rise to substantial increases in knowledge, while the industry gains a competitive advantage with the expertise given by top scientists.

d) Interviews with INSERM researchers – in the field of medical sciences – revealed a specific difficulty in the articulation between pure science and societal applications: the quite different time frames in the respective activities. In the fight against epidemics like Ebola or Covid-19 the urgence of the response requested from the health institutions is evidently not compatible with the rate of accumulation of knowledge in the research sector. INSERM is supposed to innovate in terms of medical protocols, but the chain from basic research to usages is long and fragile. In the applied sector of health, the issues are time-to-market reduction, security concerning the failure of clinical trials, economic constraints like reimbursement for treatment by health insurance, etc. It is necessary to mobilize skills across the entire health value chain leading to the design of therapies and medical devices. In the new research programs the patient is put at the center of the relationship between academic researchers and manufacturers. In a way we can consider that the patient brings new questions to research and may highlight stimulating anomalies. He/she allows the acquisition of useful knowledge simultaneously for science and industry, following a model of creativity close to that of Chesbrough at al. (2006) – *open innovation* model where creativity is distributed among many actors, including users, instead of being exclusively the output of an R&D department.

e) In the field of energy, we met IFPEN researcher. This public lab is concerned with nine scientific challenges reflecting most of the socio-economic issues in the production and use of energy (fossil and renewable energies, mobilities, climatic and environmental questions). The website states that "from research to industry, technological innovation is central to all its activities". The structuring of basic research around S&T major issues brings greater transparency and helps creating bridges between the areas of expertise. Then the scientific questioning can be shared among all academic researchers as well as with industry. It enables IFPEN to initiate scientific collaborations with firms like TotalEnergies, PSA, EDF, etc., in particular via industrial agreements for Ph.D. training – using the national CIFRE procedure (industrial agreements for Ph.D. training between academic labs and firms) which is co-financed by the government.

f) An interview at the CEA's Very Large Computing Centre completed our exploration of the science-industry relationship leading to breakthrough innovation. The collaboration agreement with a large firm has been based, since the beginning of the 2000ies, on the following co-development scheme: the computer code is designed by the CEA researchers, and the machine structure by the industrial company Bull (now ATOS who acquired Bull). The latter gained in economic standing and ATOS has since become an international leader in the field. The collaboration is still going on and the partners discuss new requirements, operate new architectures and develop services to better meet market needs.

4.2 The industry point of view

a) Let's start with a very innovative subject, at the cutting edge of science and technology: the quantum revolution. In the race for *quantum computers*, the R&D engineer from industry is at the center of a bundle of prescriptions and usages. He/she is located in the middle of the chain, benefiting from the technical specifications provided by academic researchers to design quantum computers while working on empirical cases with the industrial user communities (the early adopters) ready to co-design these technologies in order to adopt them more easily. Typically, the interested users are biologists, researchers of the pharmaceutical industry, or specialists of finance. Quantum physics is a fantastic domain, but still relatively far from practical applications. For this reason, ATOS has set up a scientific committee including a Nobel Prize (Serge Haroche) and a Fields Medal (Cédric Villani) for a quantum computing program named “Quantum”. Physicists from the scientific committee helped the firm to take the middle step of a quantum simulator before effectively getting to the real quantum computer, and this simulator has found its market.

b) In the field of *software*, the analysis of the Microsoft case (in France) is particularly interesting. A partnership between Microsoft researchers and academic researchers began with the agreement of two friends Gilles Kahn, director of the French institute for research in computer science and automation (INRIA), and Andrew Herbert, director of Microsoft Research at Cambridge, who decided to create a joint laboratory in 2007. This partnership has developed over the years in new directions, particularly around AI technology and machine learning, with applications in concrete areas. Applications could be extremely varied such as the processing of data associated with tumors in oncology or that linked to the preservation of the architectural heritage of humanity in the field of archaeology. The collaboration within a joint public/private laboratory allowed the researchers to better understand the fundamental properties of the software and, at the same time, to learn how to adapt the software to specific applications – medicine, archaeology, and many more. The researchers realized that the confrontation between different disciplines allowed them to open up the scope of their questions. The impact was twofold: new products, new services and new techniques on the one hand, and scientific results (in several disciplines) on the other hand.

c) Other examples of firms’ innovation in partnership with basic research can be given in the application field of environment, where policies and regulatory frameworks put pressure on manufacturers to innovate with the help of the scientific community. The REACH (Registration, evaluation, authorization and restriction of chemicals) initiative of the EU proposes aims at improving the protection of human health and the environment through the better and earlier identification of the intrinsic properties of chemical substances. It has modified the roadmap of many large industrial groups. The CEA exhibits an interesting case of partnership in this domain, with researches on *supercritical fluids.* Its basic research helped to shorten the time to market for many applications, like industrial cleaning/decontamination systems. Other cases concerning CEA concern *health and wellbeing* in relation with sport. A partnership with Decathlon aimed at adapting electronic devices to the practice of running, swimming, etc. Here, innovation is encouraged, through public collaboration, as a way to adapt existing commercial activities to new social requirements (public health). An interesting economic observation in this field of societal or green innovation is the sectoral restructuring: while most of the firms tend to think strategically in terms of mono-industry, the collaboration with scientific labs pushes them to develop generic multi-applications technologies (Hooge *et al.*, 2016).

5. Difficulties in the implementation of academic/industrial partnerships and ways to overcome them

We have underlined, so far, the importance of synergies between science and industry for bypassing fixation biases and promoting creativity and innovation, but several obstacles to the collaboration were mentioned during the interviews. Main issue: it is not always easy to get academic and industrial researchers to work together on the same project because, as already said, the motivations are not the same: the "beauty of science" (but also the need of publications!) *versus* the return on investment.

As a related aspect: the clocks between fundamental and applied research are not well synchronized. The understanding of natural phenomena often requires long investigations by roundabout paths, while the industrial world is focused on reducing time to market to stay competitive. The researcher in basic sciences can be satisfied by discovering a phenomenon that he/she did not expect, while the R&D engineer seeks more an answer to a precise question. So, the issue of risk is not approached in the same way, which begs the question of the funding of basic research in cooperation. Furthermore, the sharing of intellectual property between public and private laboratories is a delicate subject that needs to be anticipated before the establishment of collaboration.

Many difficulties that we have identified relate to the innovation ecosystem organization. The issue of increasing the capacity to collectively explore the unknown must be raised at an institutional level (*e.g.* firm, institute, nation, Europe). This requires an organization of research that goes beyond *research-push* or *market-pull* models, and promote *simultaneous discovery-invention research orientation*.

Without completely answering these questions which fall outside the scope of our article, we identified – on the occasion of the interviews – *cooperation models* deemed to be effective. We can mention partnership research contracts, mixed laboratories, co-development of cutting-edge instruments, associative forms, interactions with start-ups, etc. A very efficient tool in the French system is the CIFRE agreement.

Our different case studies also showed the differences – following the scientific and industrial domains – in the factors facilitating the implementation of the *discovery/innovation* general model. The conclusion below sums up several ways to overcome the difficulty of implementing the model, but it is important to underline here that every scientific discipline and every industrial context (branch, size and type of organization, etc.) constitutes a specific case. No universal strategies nor policy instruments do apply.

Conclusion

In this paper, we reinforced the idea that researchers' creativity increases when they participate in simultaneous discovery-invention research projects. The collaborative experiences we have so far observed indeed confirm the idea that an effective innovation process is rarely linear. The classical science-pushed and demand-pulled theoretical models do not apply, at least for disruptive innovation, and the Kline-Rosenberg chain-linked innovation model needs complementary precisions concerning the interaction of research and innovation producing both academic and industrial impact. New ideas and subsequent applications often emerge when different actors bring complementary and independent skills to co-create interesting solutions (cf. Figure 5).

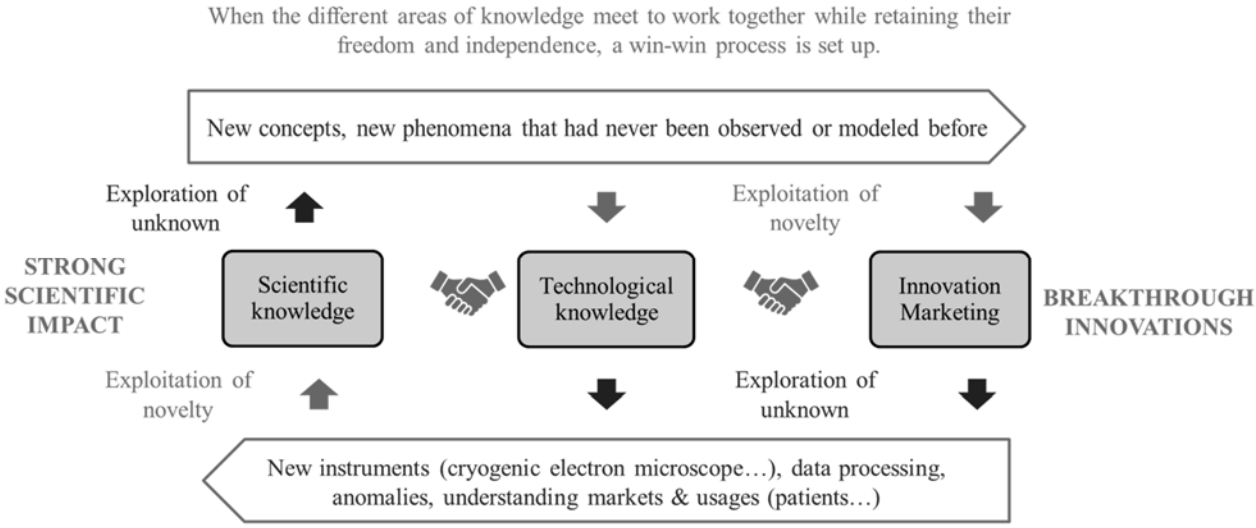

Figure 5: The simultaneous discovery-invention research model

Our different case studies have shown the differences concerning the factors facilitating the convergence between academic and industrial objectives. Globally we identified the following opportunities:

- The existence of public/private joint labs prior to the project;
- Participation of academic researchers in industrial boards;
- Doctoral training internships in parallel to collaborative agreements;
- Continued relationship in the long run between prominent researchers and their previous Ph.D. students;
- Individual characteristics: capability to act as a boundary planner (a specific aspect of individual creativity);
- Instrumentation is often the privileged link between academic and industrial worlds;
- Industrial activity can play the role of real size experiments for certain disciplines;
- Urgency situations can force the move to science-industry real-time collaborations;
- With demanding standards in terms of safety or environmental pollution, regulations force industry (e.g. chemical or nuclear) to innovate. The dissemination of these innovations is facilitated by basic research because science allows a better understanding of pollution and cleaning mechanisms, brings new quality standards, and involves the development of more reliable and efficient measurement protocols.

However, we have highlighted a number of difficulties in creating synergies between basic research and applied research (differences in individual and institutional motivations, in the perception of science, of risk, and of time). So, for promoting simultaneous discovery-invention research model, these problems should probably be addressed at the institutional level. The lessons learned from successful case studies and the researcher's reasoning analysis should help us to identify the key criteria of success for collaboration, and implement the appropriate institutional arrangements. The objective is to promote a double impact of research: a scientific and a socio-economic impact. The socio-economic impact focused on *sustainability-oriented innovations* should be considered as a priority to promote the post-Covid-19 world. This is indeed the issue of transitioning towards a world that is more respectful of the environment and in which we live in better health and with more liberty!

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