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A Model of Breakthrough Innovation: Simultaneity of Discovery and Invention

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ABSTRACT

We check the existence of cross-fertilization mechanisms between academic and industrial research in specific cases of a high creativity level and aim at describing the simultaneous discovery-invention process taking place. The classic models of innovation do not apply in these circumstances. We try to define a new model and test its relevance through testimonies of actors from public research organizations as well as industrial R&D departments. We observe various dimensions of knowledge co-creation and analyze the difficulties to overcome in these cooperative schemes. Success is not guaranteed because of institutional resistance and differences in individual motivation. If successful, the cooperative scheme considerably increases the level of global creativity and the likelihood of breakthrough innovations.

KEYWORDS: Breakthrough Innovation, Academy-Industry Partnership, Knowledge Co-Construction, Creative Management, Actors' Testimonies

JEL CODES: O31, O32

Over the last few years, several major events have pushed toward an adjustment of our socio-economic system in response to such challenges as the Covid-19 pandemic, 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, such as health, environment, energy, transportation, agriculture, etc. Most of the developed countries are considering how to redesign their research agenda to tackle these new challenges. To give an example of the multiple ways science can help to solve very concrete issues, thanks to adequate generalized vaccination we could avoid the

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sacrificial dilemma of "social distancing" *versus* propagating the pandemic. The medical problems linked to SARS-CoV-2 are not completely solved, but with the help of breakthrough technologies based on cutting-edge scientific discoveries it was possible to avoid the Chinese situation in the US and in Europe. Another example is the global economic growth dilemma: research in science and technology is expected to bring solutions for the protection of the planet without departing from our usual social contract concerning welfare and wellbeing. In order to avoid "sacrificial" solutions to such challenges, innovation is needed. Moreover, ordinary innovation such as incremental adaptation of the technological system is not enough: *breakthrough innovations* must help to reestablish sustainable development in a new technological and socioeconomic regime. We focus here on a category of breakthrough innovations achieved by the co-construction of knowledge between scientific and industrial actors. This scheme of innovation is far from the simplistic linear vision of the "application of science" or the "transfer of innovation", since there is not necessarily anteriority of scientific knowledge, but co-creation of discoveries, inventions, and innovations.

Implicitly or explicitly all governments count on science to find solutions to major challenges. Creativity is the way to escape problems for which we cannot find relevant solutions given the current boundaries of existing knowledge, but the difficulty for policy makers is that science cannot really be an object of planning. On the industry side, no more than in the case of 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 appropriate general conditions for research to develop interesting opportunities of discoveries as well as technical inventions that help to bring out breakthrough innovations. However, it is also true that under the pressure of exceptional circumstances, such as the recent pandemic, existing trends in scientific research can be greatly accelerated.

Since the seminal work of Rosenberg (1982), we know the importance of the co-construction of knowledge between users and producers. Chesbrough *et al.* (2006) observe that many ideas leading to innovation come from outside the innovative organizations (open innovation model). The relationship between science and innovation is part of this complex and evolutionary framework (Héraud, 2017). Innovation studies as well as science studies have shown the complex knowledge translation chains that occur in the process of ideation before the stage of discovery, invention, or innovation. The role of scientific knowledge in the innovation process is obvious, however scientists can no longer be considered as having the monopoly of the discovery: we observe a democratization of ideas, as Phelps (2013) says. Breakthrough innovations often reflect scientific advances but not always as a direct causal (one way) consequence, since many other actors participate in the creation chain leading to innovation.

We address here the issue of enhanced creativity *when discoveries and inventions are pursued within the same process* in order to bring about *breakthrough innovations*. The specialized literature on science-industry relationships (*e.g.* 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 analyses are related to specific theoretical constructs that we want to revisit here. The historical vision opposes the "science-pushed" model (Schumpeter, 1911 – *i.e.* the early work of the founder of innovation economics) to the "market-pulled" model (Schmookler, 1966). Rothwell (1994, p. 10) proposes a "*coupling model of innovation*" – a third generation model, after the technology push and the market pull – where the process going from idea generation to the marketplace goes through the evolution of the state of the art in technology as well as through an interaction with the needs of the society. This process is still a sequential process, but with feedback loops – like in the seminal contribution of Kline and Rosenberg (1986), which, curiously, Jay Rothwell does not mention in his very detailed article. Such models, in our opinion, fail to reveal all the complexity of the creative process, especially in the case of great breakthroughs. Rothwell (1994) proposes further models, up to the fifth generation, introducing interesting new types of interactions like the involvement of leading users in design and development activities. The point we raise is different: it concerns the interaction of scientific and innovative processes. We start from the hypothesis that a joint R&D project is also possible between two entities pursuing different goals – scientific *versus* economic – and leading simultaneously to discovery and invention.

As Godin (2006) pointed out, the reference framework for the management of R&D in the decades after the Second World War was very linear, therefore leaving 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 labor: "public institutions and basic research" *versus* "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 always 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 and the implicit assumption that the industrial (more generally economic) development only starts when scientific discoveries are made.

Concerning the process of scientific production, it is useful here to remember the famous Mode 1/Mode 2 distinction of Gibbons *et al.* (1994). In Mode 1, science is developed discipline by discipline, within traditional institutions such as faculties, and according to the standards and assessment systems specific to each field. In Mode 2, the approach is interdisciplinary and the research teams are organized around projects that often have specific applications or issues in mind. Clearly, the world we want to report on is of the Mode 2 type.

In the next sections we will: (1) discuss a model of breakthrough innovation that integrates scientific research and applied research; (2) present our research questions referring to the literature; (3) present our sources of information (actors and witnesses); (4) present the observations; (5) discuss the operational conditions for the realization of such innovations with active collaboration between academia and industry; (6) summarize in a figure our vision of the co-creation process involving discovery and invention.

Considering a Specific Model of Breakthrough Innovation

Let us first define the focus of our investigation. We want to discuss theoretically (and observe in recent history) exceptional cases of innovation. Exceptional does not necessarily mean *radical* in every possible sense of the word, but we exclude incremental innovation - where *a priori* recent scientific discoveries do not play a role. We use the term *breakthrough* because we insist on the *novelty* of the idea. Breakthrough innovations are considered here in relationship with important technological inventions and/or scientific achievements. Another terminology could apply: in management studies the term *disruptive* is increasingly used, but we avoid using it, in the sense of C.M. Christensen (*e.g.* “disruptive new businesses”), because in the present paper we do not address the details of the disruptive effects on organizations and market structures. We just assume that “innovation” means changing the market by addressing some needs that have not been properly addressed until now. We consider discoveries, inventions and the innovations that result from the synergy between these novelties: in such circumstances, innovation can certainly be considered as a breakthrough.

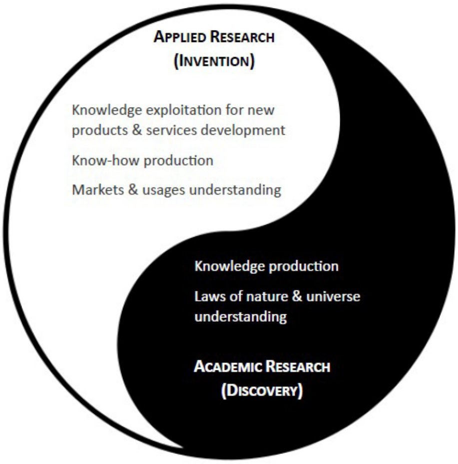
In certain cases, breakthrough innovations appear only in the domain of product/service development, but we want to underline the interesting situations where they occur in connection with scientific breakthroughs. Here the market impact is not the only effect. We observe a cluster of inventions and generally also a surge in scientific publications.

What is the *innovation model* corresponding to the field we consider? It is certainly not a linear model of the type "science-pushed" or "market-pulled" where science and innovation are not produced simultaneously. Note that this point is not purely theoretical. In terms of science policy or innovation policies there are implications, and if policymakers are not aware of such issues, they may design irrelevant policies. Héraud and Popiolek (2021) relate each model to a certain phase of 20th century history. As pointed out above, the Kline and Rosenberg (1986) model was a real conceptual advance by introducing knowledge feedbacks between many actors of the national system of innovation, but it is not certain that all the administrations have integrated it into the design of their policies more than thirty years later! And throughout this period many scholars have introduced a more complex view of innovation, drawing a non-linear scheme based on evolutionary processes in which an invention becomes an innovation, like Link and Siegel (2007). Silverberg and Verspagen (2005) proposed a percolation model of innovation in complex technology spaces. Laursen (2012) analyzed variety creation in a firm's search activities. More recently, Poutanen *et al.* (2016) address the complexity of the innovation process.

The complexity of the innovation process is clearly visible in the case of *breakthrough innovation*, where applied researchers quickly face the limits of using established scientific knowledge and need more exploratory activities (Roussel *et al.*, 1991), often in collaboration with public researchers. Building on Stokes (1997), Goldstein and Narayanamurti (2018) describe a *simultaneous discovery-invention* (SDI) 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).

In this paper we therefore consider the research field composed of two different sub-fields, *basic* (mainly academic) and *applied* (private and public) research, that have independent rationales and agendas, but usually reinforce each other. Figure 1 below presents 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 1 – The cross-fertilization between academic and applied (industrial) research: synergies to explore new fields of knowledge



Source: authors

Research Questions from the Literature

We would like to test the idea that researchers' creativity increases when they participate in *simultaneous discovery-invention* 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 major discovery. We can call it a *breakthrough discovery* in the sense that it is a discovery that happens after trying for a long time to understand or explain something, but in certain cases completely new ideas come unexpectedly during a research project that did not directly aim for this outcome. In any case a major discovery does not happen by chance; it requires the attention of a highly qualified researcher. Furthermore, in some cases the scientist had the intuition that cooperation with an external actor was necessary for the achievement. An econometric study showed that one-fifth of the studied Nobel cohort was engaged with the industry at the date of the major discovery. 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).

Hadamar (1945), who studied the psychology of 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, maximizing the output of publications may produce fixing effects, a narrowing of focus, and thus a possible reduction in the quality of exploration (Le Masson, 2020). 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).

We would like to understand to what extent academic researchers are able to ask new questions and test new hypotheses when they participate in joint projects with industry; and as for applied researchers from industry, to what extent they develop new skills and promote breakthrough innovations and other novelties that are desirable for the society. Why and how does collaboration help all the actors to succeed in their respective agendas?

The test of success for science-technology-innovation co-creation is to achieve a paradigm shift in the field of knowledge and in the market or society.

Our Sources of Information: Actors and Witnesses

We interviewed researchers from public research organizations (PROs) and industrial laboratories to highlight through specific examples how the two can work together to increase the level of creativity in a specific field of knowledge (science and/or technology) and in the economic activity. We are looking for research with a double impact: in the field of science and technology and in the socio-economic system. Innovation will be considered a real breakthrough if it depends on a completely new scientific and technological approach, and if it has a significant impact on society.

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 July 2018 to March 2019 (see Annex 2 for details about the interviews). Following these interviews, two round table discussions in which we participated were organized during a feedback seminar (Archambault, Popiolek, 2020). The first one, led by Pascal Le Masson, focused on partnership models favoring the double (scientific and socio-economic) impact (Le Masson, 2020), and the second one, led by Pierre Bitard, analyzed in a more institutional way how to promote the relationship between science and industry in a research and innovation ecosystem (Bitard, 2020).

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 by asking interesting questions for their research. We do not consider the 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 (Brown, Duguid, 1991; Amin, Cohendet, 2004).

Note that the experiences studied correspond to a pre-Covid period. In the case of health applications, it is clear that the process of innovation has very recently been enhanced with breakthroughs in pharmaceuticals, thanks to cutting-edge instrumentation. This recent period is not considered in the testimonies, but we cannot ignore the major impact of advances in cryo-microscopy and structural biology since 2020.

The institutional sample was made up of three types of actors depending on whether they belong 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 narrow community. They had to explain how this relationship led to an inventive path and helped them to innovate, sometimes in a radical way, but at least successfully tested as a new product or service that can be sold. In some cases, radical changes in science and technology may not yet have translated into radical transformations in terms of markets. In these cases, breakthrough innovation has not yet been fully demonstrated. 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.

The Observations

We looked for testimonies both in the *academic world*, which is mainly aiming to contribute to basic science, and in 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 and the industrial point of view, although we advocate for the model of co-creation in the fields of science and technology for each radical advance (double impact). In fact, the entry point is the type of interviewee who aligns with this co-creation.

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. The discovery is the Giant magnetoresistance (GMR), and the associated innovation is a radical change in hard disk technology via 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 the Solid Physics Laboratory of Paris-Sud university and that of Alain Friederich at the Central research laboratory of the Thomson CSF company (now Thales). See Verbatim 1 in Annex 1.

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 on 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 along naturally since he was a former doctoral student of Fert. Furthermore, the engineer had kept a passionate interest in theoretical physics.

This example of cooperation between university and industry shows how a sophisticated technology leads to the possibility to test hypotheses in the field of physics, generating a strong scientific impact and simultaneously a socio-economic impact via a major innovation in the electronic industry (Archambault, Popiolek, 2020). The sociological aspect of the story is the possibility generated 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* (see Tushman, 1977; Cohen, Levinthal, 1990; Cohendet *et al.*, 2013) for the co-construction of competences and knowledge.

This case is a perfect example of science-based technological breakthrough coupled with a host of innovations - including the famous MP3 applications.

b) An interview at CEA confirms the role of instrumentation in the co-development of basic and applied knowledge. Instrumentation is essential for *big science* – typically particle accelerators. In this domain, as compared to 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 big science. Researchers in basic 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 the researchers' dream is confronted by 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 opens the door to significant innovations which will subsequently spread in the consumer industry. See Verbatim 2.

Medical research and biology have also recently given good examples of co-construction, with the race for vaccines needed to fight the pandemic. Basic science and applications are developed in parallel and the role of heavy equipment also appears crucial here, since nothing could have been done without cryogenic electron microscopy. To be precise, the issue was not only founded on the existence of firms 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 to operate and use it.

These advances in physics (instrumentation) and biology are intrinsically linked. The instrumental approach is new and without it, it would be impossible to characterize the coronavirus with its spikes, and therefore to produce vaccines in record time (a breakthrough medical innovation).

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 interface between science and innovation is 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 geological subsoil exploration, such as geothermal energy, carbon capture and storage, or wastewater management. Our interviewee explained that geology is a descriptive science, modelling geological objects, in contrast to 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 offer 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. See Verbatim 3.

This kind of cooperation between fundamental research and industrial research fits in perfectly with our approach to co-creation. However, it remains to be proven that the oil industry has undergone a genuine breakthrough innovation. It is possible that the cooperation model will produce more incremental innovations (efficiency in exploration) than breakthrough innovations. Only time will tell.

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 urgency of the response requested from 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 applications 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 treatments 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. The patient allows the acquisition of useful knowledge simultaneously for science and industry (double impact), following a model of creativity close to that of Chesbrough *et al.* (2006) – an *open innovation* model where creativity is distributed among many actors, including users, instead of being exclusively the output of an R&D department. See Verbatim 4.

This area of interaction is clearly a case of distributed creativity, but only a detailed study will enable us to settle the question of breakthrough innovation.

e) In the field of energy, we met an 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, mobility, 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 major S&T issues brings greater transparency and helps create 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 PhD training – using the national CIFRE procedure (industrial agreements for PhD training between academic labs and firms) which is co-financed by the government. See Verbatim 5.

This is a typical application of the (globally successful) French policy of cooperation between industry and academic laboratories, but only in-depth studies will enable us to characterize the emergence of breakthrough innovations.

f) An interview at the CEA's Very Large Computing Center completed our exploration of the science-industry relationship leading to breakthrough innovation. Their collaboration agreement with a large firm has been based, since the beginning of the 2000s, on the following co-development scheme: the computer code is designed by 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 their field. The collaboration is still ongoing and the partners regularly discuss new requirements, operate new architectures and develop services to better meet market needs. See Verbatim 6.

We consider this case to be a genuine breakthrough innovation.

The Industry Point of View

a) The first industry example is a very innovative subject, at the cutting edge of science and technology: the quantum revolution. In the race for *quantum computers*, industry R&D engineers are at the center of a package of prescriptions and usages. They are 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, pharmaceutical researchers, or finance specialists. Quantum physics is a fantastic domain, but still relatively far from practical applications. For this reason, ATOS has set up a scientific committee including two academic physicists – a Nobel Prize winner (Serge Haroche) and a Fields Medal winner (Cédric Villani) – for a quantum computing program named “Quantum”. Physicists from the scientific committee helped the firm to take the intermediate step of a quantum simulator before effectively getting to the real quantum computer, and this simulator has found its market. See Verbatim 7.

We see these developments in quantum physics as potentially a perfect example illustrating our model, but we need to wait for the applications to be fully developed to be sure that there is innovation.

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 concerning AI technology and machine learning, with applications in concrete areas. Applications could be extremely varied, such as the processing of tumor data in the field of oncology, or data linked to the preservation of the architectural heritage of humanity (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 domains – medicine, archaeology, and many more. The researchers realized that the confrontation between different disciplines allowed them to widen 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. See Verbatim 8.

As in the previous example, it is probably a little early to be talking about breakthrough innovation, because AI applications are far from being fully implemented. However, AI is in the process of becoming a truly cross-disciplinary technology, and in this sense it represents a real breakthrough.

c) Other examples of firms' innovation in partnership with basic research can be given in the application field of the 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 aims to improve 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 research on *supercritical fluids.* Its basic research helped to shorten the "time to market" for many applications, for example industrial cleaning/decontamination systems. See Verbatim 9.

Other cases handled by the CEA concern *health and wellbeing* in relation to sport. A partnership with Decathlon is 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). See Verbatim 10.

An interesting economic observation in this field of societal or green innovation is sectoral restructuring: while most of 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).

This category of innovation shows the value of combining creativity between research in scientific institutions and organizations, whose objective is practical applications, but the radical nature of discoveries and innovations remains to be measured.

Implementation of Academic/Industrial Partnerships: Hindrances and Solutions

So far we have underlined 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. The 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 for publication!) *versus* the return on investment.

As a related aspect: the timelines 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 is not expected, 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 carefully thought through before the establishment of collaboration.

Many difficulties that we have identified relate to 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 promotes *simultaneous discovery-invention research orientation*.

Without completely answering these questions, which fall outside the scope of our article, we identified – through 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.

The different testimonies also showed the differences – following the scientific and industrial domains – in the factors facilitating the implementation of the *discovery/innovation* general model. We sum up below 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 context. No universal strategies nor policy instruments apply.

Globally we identified the following opportunities – by which we mean organizational opportunities facilitating dual impact research leading more easily to breakthrough innovation:

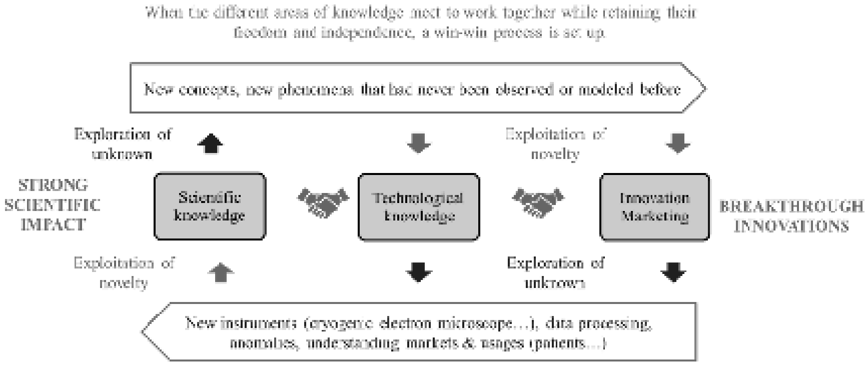
- The existence of public/private joint labs prior to the project;
- Participation of academic researchers in industrial boards;
- Doctoral training internships in parallel to collaborative agreements;
- Continued relationship in the long run between prominent researchers and their previous PhD students;
- Individual characteristics: capability to act as a boundary planner (a specific aspect of individual creativity);
- Instrumentation as the privileged link between academic and industrial worlds;
- Industrial activity can play the role of real size experiments for certain disciplines;
- Urgent situations push toward more science-industry real-time collaborations;

Let us explain the last point. With demanding standards in terms of safety or environmental pollution, regulations force industries (*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 leads to the development of more reliable and efficient measurement protocols.

The Process of Simultaneous Discovery-Invention

The figure below shows how the exploration and exploitation phases combine to create novelty. Knowledge acquired in industry (sometimes embedded in instruments) is exploited by science to explore the unknown and create new knowledge. This knowledge, like new concepts or new phenomena, is exploited in turn to give rise to inventions (technological knowledge) that the industry will be able to use. On the market side, the industry that analyzes uses is well placed to explore new economic models and creates new knowledge likely to bring new questions to science.

Figure 2 – The simultaneous discovery-invention research model



Source: authors

Conclusion

In this paper, we have supported the idea that researchers' creativity increases when they participate in *simultaneous discovery-invention research projects*. The empirical observations given point in any case in this direction. Of course, this selection of testimonies does not constitute proof. We did not build a demonstration with a control sample. The interaction of research and innovation producing both an academic and industrial impact (*cf.* Figure 1) was simply illustrated by the case studies. Our goal was to show the interest of developing a new innovation model that fits a certain number of breakthrough innovations. This model is a more complex vision that simultaneously integrates the scientific and economic progress. We advocate for the idea that new scientific knowledge and subsequent applications often emerge when different actors bring complementary and independent skills to co-create interesting solutions to existing problems (*cf.* Figure 2).

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. To promote a simultaneous discovery-invention research model, these problems should probably be addressed at an institutional level: institutional arrangements in the organizational strategy of the firms, as well as in the design of smart public policies. Promoting a double impact of research (in scientific and socio-economic spheres) is the objective for this particular type of *breakthrough innovation*. We certainly have a particular need for innovation of this kind in the current transition period (climate, environment, health, safety, etc.), because the societal response often involves a paradigm shift, and scientific knowledge remains an essential asset for achieving this. This is the meaning we want to give to the idea of breakthrough innovation in this article.

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Annexes

Annex 1 – Verbatim

These statements were made by the actors during interviews or in round tables - at seminars we organized. The ten original verbatim were in French, and we present them translated into English by us (with the very relevant help of DeepL).

Verbatim 1

> "The discovery of the giant magnetoresistance (GMR) at the very beginning of 1988 was the result of this collaboration between

> my team at the LPS in Orsay and that of Alain Friederich at the Thomson-CSF LCR. This collaboration had been initiated by a discussion between actors from both sides. The discovery came from the meeting of ideas in fundamental physics and progress in industrial technology. The discovery of GMR, with its potential for applications, triggered an intense research activity which, within a few years, led to the development of the new type of electronics known as spintronics". Albert Fert (interview: September 18, 2019).

Albert Fert is Emeritus Professor at Université Paris-Sud, scientific director of the joint CNRS/Thales lab (UMR137). Nobel prize in physics 2007.

Verbatim 2

> "The needs of the researcher, who wants the ultimate performance, therefore force the system to innovate. The research world asks industry for instruments, but works with it to define these instruments at the limit of the state of the art. The result is co-construction, which aims to obtain the best possible instrument. [.../...] Co-design allows everyone to overcome their own constraints and turn them into an innovation driver". Philippe Chomaz (Round Table: March 22, 2019).

Philippe Chomaz is scientific director at the CEA, Department of Basic Research.

Verbatim 3

> "We have developed the Source to Sink program with Total, which manages an ecosystem between Total's teams, the BRGM teams coordinating the program, and an entire French and international scientific community, around a geological object that is a sedimentation basin north of the Pyrenees. We are working jointly with the industrial company and its data on the characterization of this object to define its properties. It is likely that we will not generate industrial property as such, but rather a cognitive advance on objects that Total will be able to reuse in terms of knowhow and expertise for its teams. This is a slightly less codified relationship than our usual partnerships, but one that is extremely valuable to us: it advances fundamental knowledge, while the industrialist

> gains a competitive advantage in terms of expertise". Philippe Freyssinet (Round Table: March 22, 2019).

Philippe Freyssinet is Director of Strategy, Research and Communication at BRGM.

Verbatim 4

> "The example [of the research on Ebola undertaken by INSERM] illustrates well the interest of a good understanding of uses in the development of an innovation. The double impact, academic and industrial, goes hand in hand with a therapeutic impact and leads to giving the patient his or her full place (role). It should be emphasized that this can lead to new research questions, not only in the human and social sciences but also in other disciplines. Because this work on uses can lead to the exploration of other therapeutic paths against certain diseases or other galenic forms for a molecule". Franck Lethimonnier (Round Table: March 22, 2019).

Franck Lethimonnier is Director of the Thematic Institute Technology for Health, INSERM.

Verbatim 5

> "For some years now, IFPEN's scientific department has been structuring fundamental research into scientific locks. We have identified nine locks, for example on the effect of confinement on a number of properties. These locks are themselves broken down into challenges. [For example, if we ask ourselves about the role of diffusion in a confined environment, the question concerns both porous environments linked to the theme of geological storage of CO_2 and catalysts used for the transformation of biomass. And this scientific questioning can be shared both with our academic colleagues and with industry. This readability has also enabled us to start collaborating on fundamental research points with industrialists: Total, PSA, or EDF… via CIFRE PhD theses, for example". Yannick Peysson (Round Table: March 22, 2019).

Yannick Peysson is project manager at IFP Énergies nouvelles.

Verbatim 6

> "Discussing [with industrialists] allows us to anticipate the evolution of applications and software in order to use the technologies of tomorrow. From the CEA's point of view, this is very useful, as it brings us face to face with needs and themes that we might not have tackled straight away. […/…] The discussions also help us to define new services that will then be used in the academic, defense, and research and technology computing center (CCRT) environments". Christine Ménaché (Round Table: March 22, 2019).

Christine Ménaché is in charge of the Very Large Computing Center, Military Applications Department, CEA.

Verbatim 7

> "Quantum physics faces fundamental problems, and practical applications are still a long way off. The idea of the quantum computer therefore poses many difficulties. [.../...]. The scientific council has helped us not to oversell quantum computing at all costs. [.../...] and helped us to opt for the intermediate stage of a quantum simulator before actually arriving at the quantum computer. And this simulator has found its market". Philippe Duluc (Round Table: March 22, 2019).

Philippe Duluc is Technical Director for Big Data and Security at Atos.

Verbatim 8

> "We realize that it is through the confrontation between different disciplines that we manage to make progress on a subject, and possibly on several subjects, because we open up the field of questioning. […/…] In oncology [for example], data is extremely limited in quantity. This leads to the development of machine learning based on weakly supervised methods. Oncology is leading us to explore new areas within artificial intelligence". Bernard Ourghanlian (Round Table: March 22, 2019).

Bernard Ourghanlian is Technical Director and in charge of security at Microsoft France.

Verbatim 9

> "For the record, REACH aims to make the manufacture and use of chemicals in industry in the European Union safer. Its most immediate consequence is that waste has had a cost. From then on, reducing the production of waste or learning how to recover it had a real technical and economic interest. Green chemistry was suddenly on the map. And some companies invested in this subject to gain a strategic advantage. In just a few years, we went from disinterest to an obligation, and from an obligation to a strategic investment, with all that this implies in terms of R&D". Stéphane Sarrade (Round Table: March 22, 2019).

Stéphane Sarrade is Deputy Director of Nuclear Innovation at CEA.

Verbatim 10

> "Innovation is our playground. [.../...] We follow societal developments and work in collaborative mode. For example, we worked with Movea in collaboration with the CEA to develop connected products, which enabled us to have sensors integrated into an Artengo product". Vincent Duminil (interview: September 4, 2018).

Vincent Duminil leads the project "Easy to learn" and is Tennis Material Product Engineer, Artengo, Decathlon.

Annex 2 – Accurate information about interviews

The interviews took place over several months. 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. The date of the first interview is indicated in the table below. Some interviewees had the opportunity to speak again during a feedback seminar which we organized, and which took place at the INSTN/CEA Saclay in March 2019. Others formally expressed their point of view only during the seminar by taking the floor during a round table discussion prepared with them beforehand.

Table – Accurate information about interviews

Verbatim number if applicable	**Interviewee**	**Position at time of interview**	**Date of first interview and time spent interviewing**	**Participant at the first Round Table[1]**	**Participant at the second Round Table[2]**	**Interview location (France)**
1	Albert Fert	Emeritus Professor at Paris-Saclay University, Scientific Director of the **CNRS/Thales** Joint Physics Unit, 2007 Nobel laureate in Physics	September 18, 2019 *2 hours 30*			Thales 1 Avenue A. Fresnel 91767 Palaiseau
2	Philippe Chomaz	Scientific director at the **CEA** Department of Basic Research	July 25, 2018 *2 hours*	YES		CEA Saclay 91191 Gif-sur-Yvette
3	Philippe Freyssinet	Director of Strategy, Research and Communication at **BRGM**	Preparation of the Round Table, March 2019 *About 1 hour*	YES		By phone
4	Franck Lethimonnier	Director of Thematic Institute Technology for Health at **INSERM**	September 13, 2018 *2 hours 30*	YES		INSERM 101 Rue de Tolbiac 75013 Paris
5	Yannick Peysson	Project manager at **IFPEN**	July 11, 2018 *2 hours*		YES	IFPENon 1-4 Av. du Bois Préau 92852 Rueil-Malmais

Verbatim number if applicable	**Interviewee**	**Position at time of interview**	**Date of first interview and time spent interviewing**	**Participant at the first Round Table**[1]	**Participant at the second Round Table**[2]	**Interview location (France)**
6	Christine Ménaché	Head of the Very Large Computing Center at the **CEA** Military Applications Department	June 15, 2018 *2 hours*		YES	CEA DAM Île de France Bruyères-le-Châtel 91297 Arpajon
7	Philippe Duluc	Technical Director for Big Data and Security at **Atos**	Preparation of the Round Table, March 2019 *About 1 hour*		YES	By phone
8	Bernard Ourghanlian	Technical director and in charge of security at **Microsoft France**	Preparation of the Round Table, March 2019 *about 1 hour*	YES		By phone
9	Stéphane Sarrade	Deputy Director of Nuclear Innovation at **CEA**	July 6, 2018 *2 hours 30*	YES		CEA Saclay 91191 Gif-sur-Yvette
10	Vincent Duminil	Tennis Material Product Engineer at **Decathlon**	September 4, 2018 *2 hours*			By phone
	Clarisse Angelier	General Delegate at **ANRT**	Preparation of the seminar, March 2019, *2 hours*			ANRT 33 Rue Rennequin 75017 Paris

Verbatim number if applicable	Interviewee	Position at time of interview	Date of first interview and time spent interviewing	Participant at the first Round Table[1]	Participant at the second Round Table[2]	Interview location (France)
	Xavier Averty	Head of the Valuation Program and Intellectual Property Manager at the **CEA** Nuclear Energy Department	September 6, 2018			CEA Saclay
			2 hours			91191 Gif-sur-Yvette
	Michel Bouleau	Ethics and Expertise Project Manager at **BRGM**	September 6, 2018			By phone
			1 hour 30			

Verbatim number if applicable	Interviewee	Position at time of interview	Date of first interview and time spent interviewing	Participant at the first Round Table[1]	Participant at the second Round Table[2]	Interview location (France)
	Nathalie Brunelle	Program Director at **TotalEnergies**	Preparation of the Round Table, March 5, 2019 *about 1 hour*	YES		By phone
	Philippe Carles	Project Manager at the **CEA** International Relations Department	June 12, 2018 *1 hour*			CEA Saclay 91191 Gif-sur-Yvette
	André Gueyne	Head of Provence-Alpes-Côte d'Azur regional actions at **CEA**	July 9, 2018 *2 hours*			CEA Cadarache 13108 St Paul lez Durance
	Corinne Hueber-Saintot	Research Valorization Director at **CEA**	September 5, 2018 *2 hours 30*		YES	Centre Nano-Innov 2 Bd Thomas Gobert, 91120 Palaiseau
	Michel Mortier	General Delegate for the Valorization of Research of the **CNRS**	June 29, 2018 *3 hours*			CNRS 3 Rue Michel-Ange 75016 Paris
	Philippe Roy	Deputy delegate in charge of Research Innovation Development Projects at the **CAP Digital Pole**	July 12, 2018 *2 hours 30*		YES	By phone
	Françoise Touboul	Director of Sustainable Development at **CEA**	July 6, 2018 *2 hours 30*			CEA Saclay 91191 Gif-sur-Yvette

1. The first Round Table, led by Pascal Le Masson, focused on partnership models favoring the double (scientific and socio-economic) impact.
2. The second Round Table, led by Pierre Bitard, analyzed in a more institutional way how to promote the relationship between science and industry in a research and innovation ecosystem.