Nobel laurates and the role of the industry in the emergence of new scientific breakthroughs

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ABSTRACT: Since the 1980s, many companies recognized for their major scientific breakthroughs (e.g., IBM, AT&T, etc.), cut their investments in fundamental research activities. In parallel, academics from public research organizations (PRO) and universities engaged more extensively with the industry through research collaborations. The conditions, determinants, and effects of academic engagement have been deeply analyzed. But, the extent to which major scientific breakthroughs of the last century have emerged either from (1) academics and researchers with no interaction with the industry or (2) from scientists interacting with the industry - either as engaged academics belonging to PRO or universities or as corporate scientists – are yet to be more systematically documented. To fill this gap, we explored the extent to which scientists from the quasi-complete cohort of Nobel laureates in Physics, Medicine, and Chemistry were interacting with the industry before their breakthrough discoveries. We designed a unique dataset of their ties with the industry based on affiliations review of 84,423 academic papers and applicant review of 5,207 patent families. First, we showed that one-fifth of the studied cohort of laureates was interacting with the industry before their breakthrough discovery. More importantly, this share is still increasing, mainly through academic engagement, while the share of awarded corporate scientists has remained stable since 1970. Second, we were able to analyze the effects of those interactions with the industry on the post-discovery period by comparing interacting and non-interacting with industry laureates’ follow-on research works. While some scientific discoveries were partly made possible thanks to Nobel laureates' industrial partners, those laureates' follow-on knowledge works were not bound to their initial sets of partners. They experienced similar knowledge diffusion-to-industry rates than other laureates but higher academic production rates and diffusion-to-academia rates. Finally, we claim that the extent to which scientific new knowledge still emerges in relation to industrial contexts in modern science has been under-evaluated and opens rooms for further research.

KEYWORDS: Scientific discovery, University-Industry collaborations, Nobel Prize, New Product Development, Knowledge absorption, Academic engagement.

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AT&T's Bell Laboratories have fourteen Nobel Prize laureates among their past employees[1] , while IBM has six[2]. Those are two well-known examples of companies that established large corporate laboratories, mainly active in the post-War period, and leading them to major scientific breakthroughs such as the transistor, the cosmic microwave, the laser, or the computer (e.g., Arora, Belenzon, & Patacconi, 2018; Buderi, 2000). However, the organization of science has been subjected to profound transformations since the 1980s (e.g., Mowery, 2009; Mowery & Oxley, 1995; Pisano, 2010). On the one hand, leading companies mainly cut-off internal fundamental research activities[3], and associated resources were redirected to more short-term and commercially-oriented projects (e.g., Bhaskarabhatla & Hegde, 2014a). The value attributable to scientific research by companies dropped: they are still willing to rely on scientific findings to produce technical knowledge but appear unwilling to invest in scientific research (Arora et al., 2018). On the other hand, scientists from Public Research Organizations (PRO) and universities have appeared to collaborate more than ever with companies: those collaborations are vital to favor new scientific knowledge, transfer, and technological innovation (e.g., Etzkowitz & Leydesdorff, 2000; Rothaermel, Agung, & Jiang, 2007). Academics have tended to be more extensively *engaged* with the industry (D'Este & Perkmann, 2011), a phenomenon practiced across all scientific disciplines and of substantial economic significance (Hughes et al., 2016; Perkmann & Walsh, 2007). It has been notably demonstrated that academic engagement has a positive effect on research productivity

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[1] C. Davisson, J. Bardeen, W. Brattain, W. Shockley, P. Anderson, A. Penzias, R. Wilson, S. Chu , H. Störmer, D. Tsui, R. Laughlin, W. Boyle, G. Smith, A. Ashkin
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[3] IBM, for example, eliminated one-third of its total R&D budget in 1993 getting from 5.1 billion dollars to 3.5 billion dollars only (Buderi, 2000)

(e.g., Banal-Estañol, Jofre-Bonet, & Lawson, 2015; Bikard et al., 2019; Gulbrandsen & Smeby, 2005; Hottenrott & Lawson, 2017), is more practiced by successful scientists in applied research (e.g., Bekkers & Bodas Freitas, 2008), with peers also engaged in such collaborations with the industry (Tartari et al., 2014).

Those major transformations in the science-industry complex have been deeply reviewed in management science. But the analysis of the industry's role in discovering major scientific breakthroughs – either by corporate scientists or by engaged academics interacting with private companies -– has received less attention. In other words, **documenting the contribution of corporate scientists and engaged academics with the industry to the total amount of significant scientific discoveries that changed our lives, in the long run, would be of interest. Moreover, exploring this phenomenon in more depth could help** to guide policymakers and practitioners.

It has to be noted first that it is established that academic engagement is largely practiced and is positively correlated to engaged academics' scientific productivity. But, the question of the relation between academic engagement and the potential for breakthrough scientific discoveries needs better scrutiny (Perkmann, Salandra, Tartari, McKelvey, & Hughes, 2021). Then, evaluating the share of major scientific breakthroughs made by engaged academics would be of interest. Second, there are some counter-intuitive examples of the recent decline of corporate R&D and the increase of academic engagement regarding major scientific breakthroughs. On the one hand, for example, CRISPR-Cas system discovery was notably made by P. Horvath and his team at DUPONT-DANISCO corporate laboratory in 2007 (Lander, 2015) and paved the way for the 2020 Chemistry Nobel Prize, Arthur Ashkin discovered the optical tweezers at NOKIA and was awarded the Physics Nobel prize in 2018. On the other hand, we can also find evidence of significant scientific discoveries made by engaged academics at the end of the 19th century. For example, Louis Pasteur discovered microbiology while being an academics at the Lille University in France and collaborating with local brewers. To better understand the dynamics of corporate scientists and engaged academics' contribution to major discoveries in the long run and at a large scale would then be of interest. Third, it has been mentioned that scientists interacting with the industry might suffer from publications restrictions or additional delays to contribute to open science due to secrecy and patenting activities (Blumenthal, Causino, Campbell, & Louis, 1996; Czarnitzki, Grimpe, & Toole, 2015). The industry may divert those scientists from curiosity-driven research (Azoulay, Waverly, & Toby, 2009; Callaert, Landoni, Van Looy, & Verganti, 2015; Van Looy, Callaert, & Debackere, 2006), implying weaken the Mertonian norms of science in academia (Mowery, 2009; Perkmann & Walsh, 2009) and limiting the potential for breakthrough discoveries. Hence, those elements could conduct to assume that the global contribution of corporate scientists or engaged academics to major scientific breakthroughs could be limited. In addition, their interactions with the industry may conduct to follow-on knowledge diffusion restrictions, a phenomenon that also would need better scrutiny.

Finally, by bridging the literature on corporate R&D and academic engagement, this article aims at **filling this gap by exploring in more depth the degree to which the major scientific breakthroughs of the last century have emerged either from (1) academics and researchers with no interaction with the industry, or (2) from scientists interacting with the industry, either as *engaged academics* belonging to PRO or universities, or as *corporate scientists.* It also intends to understand better the subsequent effects of interacting with the industry for follow-on knowledge developed by scientists who made breakthrough discoveries.** Those investigations are critical as the role of the industry in the early emergence of scientific breakthroughs has only been documented through questionnaires or case studies (e.g. D'Este & Patel, 2007; Evans, 2010; Narayanamurti & Odumosu, 2016; Stokes, 1997). The "*backward link*" (D'Este & Perkmann, 2011: 330) of interacting with the industry on fundamental research activities — either as a corporate scientist or as an engaged academic in a PRO or a university — is still underappreciated (Perkmann et al., 2021) and contentious (Murray, 2010).

To take a step towards filling these gaps, we explore the case of scientists awarded with the Nobel Prize as in the long run, as they constitute an adequate proxy of fundamental scientific activities evolution and can help us better understand modern science dynamics (Jones, 2009)[4]. We relied on a sample of 518 Nobel Prize laureates in "hard science" (Physics, Medicine, and Chemistry) who were awarded between 1902 and 2016 for their outstanding scientific discoveries. We designed a unique new dataset of Nobel laureates' ties with the industry based on databases crossing (Jefferson et al., 2018; Li, Yin, Fortunato, & Wang, 2019; European Patent Office, 2019) and text-matching technique. We carried (1) an in-depth review of 21,897 distinct affiliations or funding organizations reported in 84,423 academic papers published by Nobel laureates, as well as (2) a detailed analysis of organizations cited as applicants in 5,207 patent families that we were able to allocate as having been filled by a Nobel laureate. Indeed previous research showed that reviewing academic papers or patent affiliations with the industry constitute an adequate proxy to measure researchers' or inventors' ties with industry (e.g., Abramo, D'Angelo, Di Costa, & Solazzi, 2009).

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[4] We underline that we were not the first to rely on Nobel data, particularly since the seminal work of Zuckerman (Zuckerman, 1977). Scholars, for example, reviewed specificities of the cohort (e.g., Chan, Önder, & Torgler, 2015; Schlagberger, Bornmann, & Bauer, 2016) or used Nobel laureates' publications or patents data as benchmarking technique (e.g., Fontana, Iori, Montobbio, & Sinatra, 2020). Nevertheless, to our knowledge, we are the first study to analyze the relation between Nobel laureates' breakthrough discoveries and their relations with the industry.

Our primary contribution in this article is to establish that, 1/5 of the cohort of Nobel laureates was interacting with the industry at the date or before their fundamental breakthroughs, and this share **is mainly increasing since the 1980s**. Hence, **more than one out of two laureates awarded between 2010 and 2016** (our last period of observation) **made its scientific discovery in relation to knowledge arising from their ties with industry**. We also demonstrated that while the share of laureate awarded as *corporate scientists* since the 1970s remain roughly stable, the share of laureates awarded as *engaged academics* has been highly increasing since the 1980s. This process is also discipline dependent: a more significant number of laureates were engaged with the industry in Physics and Chemistry than in medicine, even if we observed a catch-up phase in the last couple of decades that matched with recent structural changes in the way of doing, for example, biomedical research in healthcare contexts (Anckaert, Cassiman, & Cassiman, 2020). Our second contribution concerns follow-on research works of scientists interacting with the industry. We show that although we posit that discoveries of laureates that were interacting with the industry were partly made possible thanks to their industrial partners, the laureates' subsequent knowledge was not bound to their initial sets of partners. Laureates interacting with the industry experienced similar knowledge diffusion-to-industry rates than other laureates after their breakthrough discoveries, but higher academic production rates and diffusion-to-academia rates. They are also not experiencing a more remarkable shift towards more applied research than their peers who were not interacting with the industry in the first place. We claim that those findings advocate for a renewal of the understanding of the industry's role in the early emergence of new scientific knowledge in modern science because the magnitude of this phenomenon might have been undervalued.

1. CONCEPTUAL BACKGROUND

1.1. Interaction with the industry as a catalyzer of scientific breakthroughs

As identified by Wit-de Vries (2018), the industry's role when interacting with scientists has been mainly oversimplified to the formulation of interesting research questions and the furniture of data regarding application contexts (de Wit-de Vries et al., 2018). This "*backward links [*of the technological development on the potential for new scientific discoveries is] *often under-appreciated*" (D'Este & Perkmann, 2011: 311). Here, we review two main ways by which the interaction with the industry can favor scientific breakthroughs: (1) by fueling with diverse original resources the scientific activities and (2) by creating synergies between scientists and their industrial partners through the engagement.

Regarding the first mechanism, scientists interacting with the industry may benefit from the fact that the industry is a valuable source of skills, material, equipment, resources, and ideas to fuel the **upstream process of research** (e.g. Banal-Estañol, Jofre-Bonet, & Lawson, 2015; D'Este & Perkmann, 2011; Gulbrandsen & Smeby, 2005; Lee, 2000; Mansfield, 1995; Siegel, Waldman, & Link, 2003). Indeed, scientists can be fueled by new ideas or new research questions with positive repercussions on their scientific agenda (Al-tabbaa & Ankrah, 2016; Gulbrandsen & Smeby, 2005; Hughes et al., 2016; Mansfield, 1995). For example, Mansfield (1995), in a study on 200 academic researchers, showed that half of the respondents reported that their choice of studying a given problem and the direction of their work was considerably or primarily influenced by their funders or users, with a more significant effect for scientists collaborating with the industry. In addition, the industry may also provide practical environments to test theories or ideas related to the **downstream process of research** (D'Este & Perkmann, 2011; Siegel et al., 2003). For example, Lee (2000), in a survey of over 422 faculties, showed that the reasons to engage with the industry are mostly driven by gaining research insights and, testing and applying theories instead of pursuing future commercial goals. Finally, those findings match studies on academic engagement motives that repeatedly showed that scientists mainly engaged with the industry for intellectual challenges and research purposes (e.g., Blind, Pohlisch, & Zi, 2018; Lam, 2011).

Regarding the second mechanism, the interaction itself between scientists and the industry can pertain to positive synergies and spillover effects. On the one hand, scholars reported scientists could work on projects that are sharing both applicative objectives and fundamental research questions with potential for new scientific discoveries (Stokes, 1997): basic research and applications would then be complementary (Narayanamurti & Odumosu, 2016; Narayanamurti, Odumosu, & Vinsel, 2013). Indeed, as shown in documented historical cases such as the Manhattan Project (Gillier & Lenfle, 2019) or the invention of the transistor at the Bell Laboratories (Gertner, 2012), the industry has developed an invention in the first place, but which lack of scientific understanding of the underlying phenomenon. Hence, resolving problems that arise from technology development can conduct further research activities and fuel the research agendas. For example, Goldstein & Narayanamurti (2018) reviewed the case of the Advanced Research Projects Agency – Energy of the Department of Energy (DoE), which aims at financing projects that "*bridge the gap between basic and applied research and development*" (Goldstein & Narayanamurti, 2018: 1506). They showed that ARPA-E projects conduct scientists to fill more patents and to publish more publications than any other DoE Agencies focusing either on basic or applied research. On the other hand, academia and industry differ in approaching research and using different methods and logic of reasoning, increasing the teams' creative potential (Evans, 2010; Mansfield, 1995). Indeed, interacting with the industry conducts an increase in the pool of ideas accessible by academics (Rosenberg, 1998) and increases the variety of those ideas: teams with mixed backgrounds are then more able to overcome those issues (Hargadon & Sutton, 1997; Teodoridis, 2017; Uzzi & Spiro, 2005).

Those two mechanisms demonstrate that interaction with the industry is associated with higher research performances. First, it has been shown that interaction with the industry conducts to greater academic productivity and quality (e.g., Hottenrott & Lawson, 2017; Tijssen, 2018; Zucker & Darby, 1996, Bikard et al., 2019). For example, Tijssen (2018) showed that "crossover collaborators" (measured as those who collaborated the most with the industry) have higher publications rates than those who do not, based on a case study at KU Leuven University. Bikard et al. (2019) relied on twin discoveries to explore the effects of collaborating with the industry. For a given twin discovery (Bikard, 2020), if scientists collaborated with the industry for one article, but not the scientists in its twin paper, engaged academics publish more follow-on articles on the research projects than their peers. This positive effect on ex-post publications quality and quantity is mediated by the type of collaborations, particularly if the research project is aligned with the academic's research goals (Callaert et al., 2015). Scholars also report a curvilinear relation between engagement and scientific productivity (Banal-Estañol et al., 2015). Second, mainly no shift from basic research towards more applied research has been found when reviewing the case of scientists interacting with the industry (e.g., Agrawal & Henderson, 1997; Breschi, Lissoni, & Montobbio, 2008).

As a result, when considering the conceptual mechanisms for a positive effect of scientists interaction with the industry on science, as well as the empirical analyses made on those academics performances, we could posit that a large share of scientific breakthroughs could come from scientists in relation with the industry, either from corporate scientists or engaged academics, with potential for fruitful follow-on research. Nevertheless, the literature also reported a more nuanced approach by reviewing negative drawbacks on the relation with the industry for scientific breakthroughs.

1.2. Adverse effects of interaction with the industry for scientific breakthroughs and follow-on research

Scholars studying scientists' interactions with the industry pointed out some potential adverse effects of this interaction on scientists' performances.

First, scholars raised concern that a more excellent orientation towards academic engagement would distort the institutional norms of research freedom and fast and wide dissemination of research results in science (Merton, 1973; Mowery, Nelson, Sampat, & Ziedonis, 2001). In particular, scholars reported that some companies impose publication restrictions, additional delays or may ask for secrecy on some part of the research. It conducts to more significant publication barriers for scientists involved in such interactions with the industry (Blumenthal, Causino, Campbell, & Louis, 1996; Czarnitzki, Grimpe, & Toole, 2015; David & Dasgupta, 1994; Lee, 2000; Thursby & Thursby, 2002) with adverse effects for the global innovation system. Indeed, the benefits of research work disclosure and the associated increase of the stock of public scientific knowledge have been repeatedly demonstrated (David & Dasgupta, 1994; Mukherjee & Stern, 2009; Murray, Aghion, Dewatripont, Kolev, & Stern, 2009). The value appropriation of research by private companies has been considered increasing since the 1980s due to changes in innovation systems and the Bayh-Dole act (Taylor Aldridge & Audretsch, 2011; Tijssen, 2004). Those barriers would result in a decrease of the number of publications of scholars interacting with the industry, and by then, a decrease of the diffusion rate of research towards the academia.

Second, the more excellent orientation towards research commercialization of entrepreneurial universities (Etzkowitz, 2003) may influence scholars' research agenda and activities. For example, Goldfarb, (2008) showed that scientists who maintained their relationships with an applied-oriented partner, in a study on 221 scientists involved in the NASA Aerospace engineering program in 1981, experienced a decrease in publications of academic papers during their careers. Indeed, academic engagement can divert academics from research activities as they might spend more time doing other activities (problem-solving, contract management, conflict management, etc.), affecting their scientific productivity (Yusuf, 2008). Toole & Czarnitzki (2010) even claimed that while "*these academic entrepreneurs devote significant time and cognitive effort to the firm, their contribution to academic knowledge accumulation is likely to be less—a potentially costly "brain drain" on the not-for-profit research sector*" (Toole & Czarnitzki, 2010: 1599). University-industry interactions and emphasis on commercialization can also lead to a more excellent orientation toward applied research (Slaughter, 1993). For example, in a study on 3,862 academic life scientists, Azoulay, Waverly, & Toby (2009) showed an increase in patenting for academic researchers conducted those inventors to shift their research focus towards questions of commercial interests, which is considered as having less potential for serendipity. Those mechanisms would support lower performances in terms of publications and their quality and an increase of the research diffusion to the industry due to the adoption of a more applied-oriented perspective.

2. METHODOLOGY & DATA

2.1. Identification of Nobel laureates who interacted with the industry

To collect data regarding Nobel laureates, we used Li et al. (2019) public dataset available on *Nature data*. They combined diverse sources of unstructured data such as Nobel laureates' university websites, CV's of laureates, laureates' Wikipedia pages, Nobel.org website, and the Microsoft Academic Graph (MAG) database to come up with an extensive list of 89,311 academic papers written by 92.4% of all the Nobel laureates in Chemistry, Medicine and Physics awarded between 1900 and 2016. They also identified the specific scientific paper that led each laureate to be awarded the Nobel Prize, then called *Prize paper*. This identification is based on a particular text-matching technique between laureates' scientific papers and public data regarding why the Nobel committee decided to offer them this Prize (available on Nobel.org or Wikipedia.org websites) and an assessment of laureates' scientific papers academic citations[5]. We called *Period 0,* the period between the first academic paper of a given laureate and his/her Prize Paper; *Period 1,* the period between his/her Prize Paper, and the Nobel award[6].

Then, we consider the potential interactions with the industry that the laureate may have experienced. We designed a unique dataset that relied on a review of laureates' ties with the industry based (1) on a careful examination of authors' affiliations and funding organizations of all papers written by Nobel laureates as well as (2) a review of all assignee organizations of patents filed by laureates.

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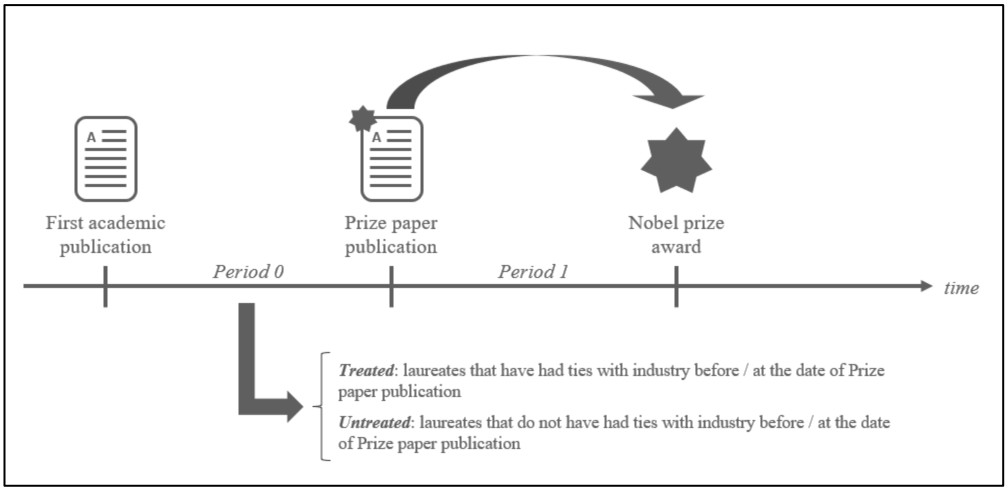
[5] When there was more than one prize paper, we selected the first published one to adopt a conservative approach.

[6] The period post-Prize has been excluded to avoid issues related to distortions of the results following the fact that the laureate become more famous and can received additional solicitations and can be diverted from research.

As described in the upper section, the literature showed that scientist who interact with the industry might have access to original resources, skills, materials, ideas, different ways of thinking, feedback, fields of experiments, or benefit from synergies with the industry. Hence, we assume that interaction with the industry in *Period 0* would have probably influenced their research works, although we cannot measure the precise magnitude of this inspiration. Because Nobel laureates are comparable scientists between each other's as their scientific discoveries can be considered as having similar magnitude, it allows us to explore the extent of this phenomenon, its evolution as well as to assess the difference in terms of knowledge diffusion and research performances between those two populations. The procedure is summarized in **Figure 1** below



Treated: laureates that have had ties with industry before / at the date of Prize paper publication

Untreated: laureates that do not have had ties with industry before / at the date of Prize paper publication

Figure 1 – Treated Nobel laureate identification process

2.2. Academic publications of Nobel laureates and industry ties

Academic publications of Nobel laureates in physics, chemistry, and medicine were gathered using Li et al. (2019) dataset who provided Microsoft Academic Graph (MAG) unique identifier for each scientific paper. Hence, based on that data key, we extracted affiliations of the laureates and all their co-authors and the funding sources of each article from the LENS project database –

scholarly work API (Jefferson et al., 2018)[7]. The LENS project[8] database crossed and harmonized academic publications' metadata, such as affiliations or funding sources from multiple databases, including MAG, Web of Science, and PubMed. It also includes, for some affiliations, a link to the Global Research Identifier Database (GRID), a publicly available dataset[9] that helps in defining and disambiguating the type of affiliations[10]. We retrieved 99.9% of the publications and selected only those from journal articles (instead of books or conference proceedings for example) and consistent meta-data regarding the laureate careers. It represents a final set of 83,372 academic papers for 518 laureates on the 590 laureates awarded between 1901 and 2016 in the three selected disciplines. Due to the diversity of affiliations and co-authors, the resulting dataset comprises c. 2.7 million entries and 21,597 different affiliations or funding organizations.

Regarding affiliations, it has to be highlighted that while we are using one of the most accurate databases, 33.3% of the academic papers are not related to any organization. Second, 83.2% of affiliations were missing from the GRID database (i.e., raw data not classified). Hence, we developed an algorithm to classify those remaining affiliations based on text-matching techniques (~ 500 words)[11]. We were then able to allocate 15,593 affiliations to a specific type: 7,911 to *Education*, 5,196 to P*ublic Research Organizations, NGO, Private Institute and Associations*, 1,498 to *Healthcare*, and finally 988 to *Company*. Therefore, the 2,567 remaining affiliations were allocated manually based on an Internet search for the organization name. For 1,343 we did not retrieve any type due to an error in the affiliation names[12]. Finally, we were able to classify 18,924

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[7] We designed a *R* program for this particular task through a R Studio interface.

[8] https://www.lens.org/

[9] https://www.grid.ac/

[10] Categories of affiliations included: Education (e.g. the University of Manchester), Government for Public Research Organizations (e.g. the Max Plank Institute), Non-Governmental Organizations (e.g. the Cancer Research UK), Healthcare (e.g. Pittsburgh Medical Center) or Company (e.g. IBM).

[11] Based on word occurrence and, when possible, we assigned them to a specific category such as Healthcare or Company. For example, all affiliations that contained "university", "school", "école", "université", "escola", etc. were classified as Education. Affiliations that contained for example "company", "GmbH", "corporation", "S.A." etc. were classified as Company.

[12] For example, affiliations recorded as "Geneva Switzerland", "New York city department"

unique affiliations (93.3% accuracy on available data). We then define whether each publication in our final dataset involved at least one author affiliated to a company representing[13] 3,422 unique publications (4.10% of all publications)[14].

We then performed an analysis to identify in each publication with the industry, if (1) the laureate was directly considered as affiliated or co-affiliated to the company or (2) if the paper was the result of a co-publication with industry co-author(s) while the laureate was affiliated another type of organizations (Education, PRO, NGO, research associations or healthcare). All publication data are finally gathered at the laureate level for each period (panel structure) and normalized.

2.3. Patent of Nobel laureates and ties with the industry analysis

Previous literature showed that academics' patents could help define ties with the industry, particularly by analyzing the applicant of the patent (e.g., Balconi, Breschi, & Lissoni, 2004; Balconi & Laboranti, 2006; Crescenzi, Filippetti, & Iammarino, 2017). However, it must be highlighted that matching scientists and patents is a complex task due to the quality of the data[15]. Here, we collected data from the PATSTAT database[16]. We looked for patents filed by inventors with similar names and surnames[17] to those from the list of Nobel laureates' academic publications. We restricted the sample to only the patents that have been filled after the first academic publication of the laureate and before his/her last known publication in our dataset. We then collected data on

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[13] After name harmonization, 661 different industrial companies interacted with our sample of Nobel laureates, including, of course, IBM and the Bell Laboratories, but also Dutch State Mines (DSM), Alcatel-Lucent, Nichia Chemical or Hoffman-LaRoche.

[14] Our data are consistent with Tijssen (2012) analysis that showed that 4.2% of Thomson Reuters' Web of Science database included at least one author from the industry.

[15] Example: how the name of the inventor is written in the patent or how would we be able to cross-validated that the academic author does not have a reduplicated names that would distort the data set. Scholars used ex-post mailing and phone calls with inventors to check the data (Balconi et al., 2004) or geocoding strategies (Crescenzi et al., 2017) as validation procedure.

[16] Spring 2019 version

[17] It includes a check for second and third first names whenever needed

application number, DOCDB family number, DOCDB applicant harmonized name, and applicant category (e.g., Company, University, Government, etc.) by relying on the PSN classification from PATSTAT (OEB, 2019)[18]. We did not control whether or not the patent has been granted as we focus on the ties with industry only. We then retrieved 38,655 patent applications that involved 308 Nobel Prize laureates.

To control for the issue of reduplicated names, we adopted a conservative approach. First, for all potential companies cited as an applicant for a given Nobel laureate identifier, we checked if the company name has been cited either in the Nobel.org webpage of the Nobel laureate (included extensive bibliographical data and Nobel laureate's lecture, for example) or in the English Wikipedia page of the Nobel laureate. Second, we checked if the company name appeared in its academic publications' affiliations of the laureate or its co-authors. Finally, all affiliations were manually checked to ensure the data's consistency, and company names were harmonized with the list gathered from the publication dataset. It then comprises 4,658 patent applications with 2,321 cross-validated with Nobel.org or Wikipedia websites and 2,478 cross-validated with affiliations data of laureates or co-authors. The final dataset includes 5,219 patent families, with 3,001 filled for company applicants and 2,394 filled for university-like applicants. In total, 185 distinct laureates from our sample have filled at least one patent family. We adopted a similar approach for patents filed by Nobel laureates for universities, public laboratories, and research associations as applicants by controlling the PSN sector (OEB, 2019). All patent data are finally gathered at the laureate level for each period (panel structure) and normalized.

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[18] We adopted an approach through patent families (DOCDB). It constitutes a better approach to inventors' creative activities by disentangling the different applications that might be filled in different countries or geographic areas (Martinez, 2010; Martínez, 2011).

2.4. Nobel laureates' research orientation

To proxy research orientation towards basic or applied research, we explored how the industry relies on laureate's academic papers when filing patents. Hence, scholars have extensively used Scientific Non-Patent Literature (SNPL): scientific publications cited by the inventor or the examiner of a given patent application to demonstrate the invention's newness. SNPL constitutes an adequate proxy of the orientation of research towards applied research. Hence, the more the industry cites an academic paper, the more the research work is oriented towards application.

Here, we relied on the Marx & Fuegi (2020) dataset as they conducted an in-depth analysis to disentangle citations to academic papers in patents filled in the USPTO, OEB, and the PCT procedure. Then, after crossing the database on Nobel laureates' publications and SSNPL, we showed that 13,935 academic papers written by Nobel Prize laureates in our sample are cited in 68,361 specific patent applications. All SNPL data are finally gathered at the laureate level for each period (panel structure) and normalized.

3. EXPLORING THE COHORTS OF NOBEL LAUREATES THAT WERE INTERACTING WITH THE INDUSTRY

3.1. Laureates interacting with the industry characteristics

We computed in **Table 1** the number of Nobel Prize's laureates with ties with the industry before or at the date of the publication of their prize paper, split by channel and discipline. First, we showed that a significant part of the cohort of Nobel laureates had ties with the industry before the publication of their prize paper: 108 Nobel laureates experienced such connections, representing 21% of the whole cohort in our sample. Second, we reviewed in what extent the laureates used a particular channel of interaction with the industry. The main channel is *academic engagement*, i.e., an academic publication in collaboration with an industrial company for which the (future) Nobel laureate is affiliated to a university-like organization for a given publication while at least one co-author is affiliated to an industrial company. Half of the laureates interacting with the industry used this channel (i.e., CI Pub.). Still, a closer number of laureates were *corporate scientists*: they wrote academic papers when being directly affiliated to an industry organization (i.e., IA Pub.) or filled patents for industry applicants (i.e., CI Pat.). Third, we demonstrated that industry interactions were divergent from one discipline to another. Indeed, while the number of laureates that had ties with industry before their prize paper is similar between Physics and Chemistry (i.e., 26%), only 13% of the laureates in medicine were interacting with the industry. The channels also vary as laureates in Physics were twice more frequently corporate scientists that engaged academics, while academic engagement tis the main channel for Chemistry and Medicine.

	Nbr. Nobel Prize's laureates *(share of the cohort)*	**Nbr. Nobel Prize's laureates** *(share of the cohort by discipline)*		
		Physics	**Chemistry**	**Medicine**
Nbr. laureates affiliated to a University-type organization who published academic papers with industry-affiliated co-authors before publishing its Nobel paper (CI Pub.)	55 *11%*	16 *9%*	24 *15%*	15 *8%*
Nbr. laureates directly affiliated with an Industry-type organization and published academic papers before publishing its Nobel paper (IA Pub.)	52 *10%*	29 *16%*	14 *9%*	9 *5%*
Nbr. laureates registered as an inventor for an Industry-type organization who filled patents before publishing their Nobel papers (IA pat.)	38 *7%*	19 *11%*	14 *9%*	5 *3%*
Engaged academics	55 *11%*	16 *9%*	24 *15%*	15 *8%*
Corporate scientists (IA Pub. + IA Pat. with no CI Pub.)	53 *10%*	31 *17%*	16 *10%*	6 *3%*
Nbr. laureates interacting with the industry before or at the date of their Nobel papers	**108** ***21%***	**47** ***26%***	**40** ***26%***	**21** ***11%***

Note: for example, 16 Nobel laureates in Physics published at least one academic paper before (or at the date) of their Prize Paper publication by being affiliated to a University-type organization while at least one co-author was affiliated to the industry in this paper. It represents 9% of the whole cohort of Nobel laureates in Physics. A given Nobel laureate can be involved in more than one channel.

Table 1 –Nobel laureates interacting with the industry split by disciplines and channels

3.2. Nobel Laureates' company partners characteristics

We explored some industrial companies' characteristics that interacted with Nobel laureates before their Prize Paper. The 108 laureates interacting with the industry had ties with 119 distinct companies. Table 3 details the average number of Nobel laureates interacting with a given company and the number of patent families or academic papers written in total by laureates in period 0 with a given company. It appears that companies in our sample collaborate on average with only 1.63

laureates. We observed that the Bell Laboratories or IBM are the tips of the iceberg. Indeed, they record many papers and patents filled by future Nobel laureates compared to the other companies. Still, a wider breadth of industrial companies worked with Nobel laureates. We also noticed that companies with ties with Nobel laureates filled 3.84 patent families and participated in 4.35 academic papers writing on average.

Period before Nobel paper (i.e. period 0)	**Obs.**	**Mean**	**Std. Dev.**	**Min**	**Max**
Nbr. Nobel laureates per industrial company interaction before their Prize paper	119.00	1.63	2.32	1	23
Nbr. academic paper wrote by Nobel laureates per industrial company interaction before their Prize paper	94.00	4.25	15.36	0	120
Nbr. patent family filled by Nobel laureates per industrial company interaction before their Prize paper	49.00	3.84	10.55	0	87
Nbr. output (patent family and/or paper) by Nobel laureates per industrial company interaction before their Prize paper	119.00	8.09	20.32	1	153

Note: The number of academic papers represents the total number of academic papers written by a given laureate as affiliated to the company, or with co-authors affiliated to the company, or with the company as a funding organization. The number of patent families represents the total number of patent families filled by Nobel laureates with the company as an applicant. The number of interacting laureates represents the number of distinct laureates that have published the latter academic papers or filled the latter patents. Those numbers are non-normalized due to company-level analysis.

Table 3 – Ties of laureates with industrial companies

3.3. Temporal dynamic of industry-inspired Nobel laureates

We analyzed the evolution through time of the share and number of laureates interacting with the industry across the sample's whole cohort of laureates. One particularity of our dataset is that we explored a very long period (from 1905 to 2016 by date of award). The science system was profoundly modified through the last century with, for example, a significant increase in the number of published academic papers and co-authors network (e.g., Arora et al., 2018; Pisano, 2010). Therefore, we reviewed the share of Nobel laureates that had ties with industry before their prize paper based on the date of award per decade basis (**Figure 2**) and by analyzing the split per discipline (**Figure 3**).

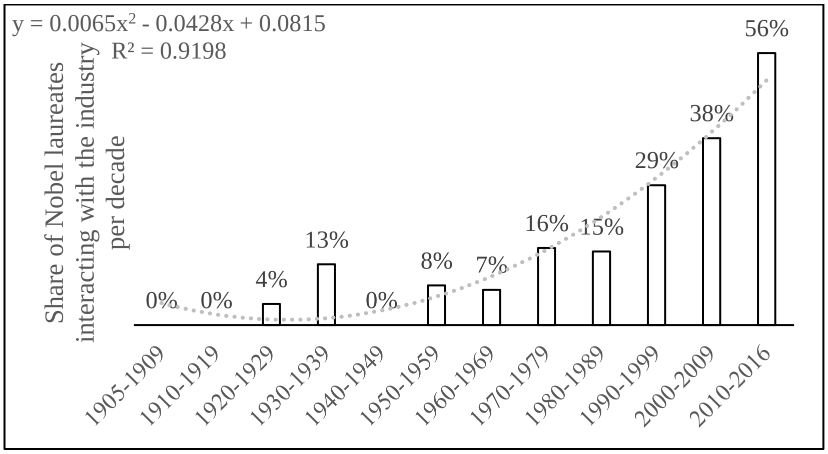

Figure 2 – Evolution of share of Nobel laureates interacting with the industry per decade and by date of award in period 0

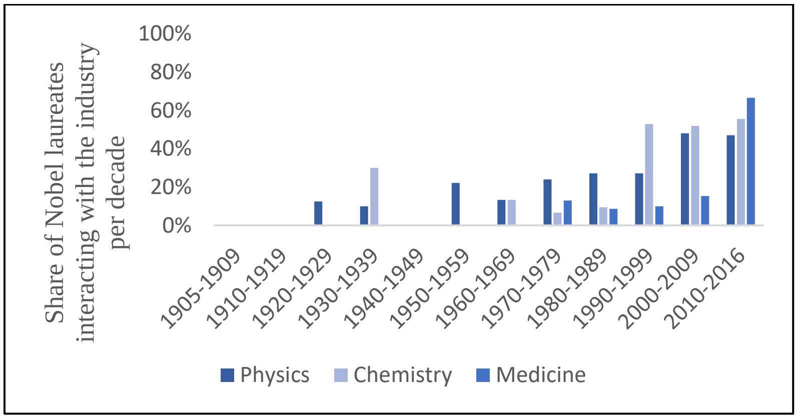

Figure 3 – Evolution of share of Nobel laureates interacting with the industry per decade and date of award and split by discipline

We observed an increase of Nobel laureates interacting with the industry since the 1960s and up to the last decade. Indeed, the share of laureates interacting with the industry was only 7% in 1960 – 1969 and rose to 56% during the period 2010 – 2016. In particular, we noticed a significant increase in the number and share of laureates interacting with the industry awarded in the 1990s and the 2000s, despite the cut in fundamental research investments operated by companies. Even by considering the lag between the prize paper and the Nobel award, the magnitude of the effect continues after the significant cuts in fundamental research. Regarding disciplinary contribution, the increase was mainly driven by Physics and then Chemistry for a relatively similar share, but surprisingly, medicine contributed mainly to the last period (2010 – 2016).

In **Figure 4**, we observe the evolution through time of the share of engaged academics, non-engaged academics and corporate scientists awarded the Nobel Prize per decade and date of award. First, we found evidence that the share of non-engaged academics at the time or before their Prize paper has been strongly decreasing since the 1980s as it has been divided by a factor of two. Second, we show that the share of corporate scientists stayed relatively stable since the 1970s with c. 15% of laureates per decade. But, the share of engaged academics awarded with the Nobel Prize largely increased since the 1970s and is even more significant than the share of corporate scientists from the 2000s.

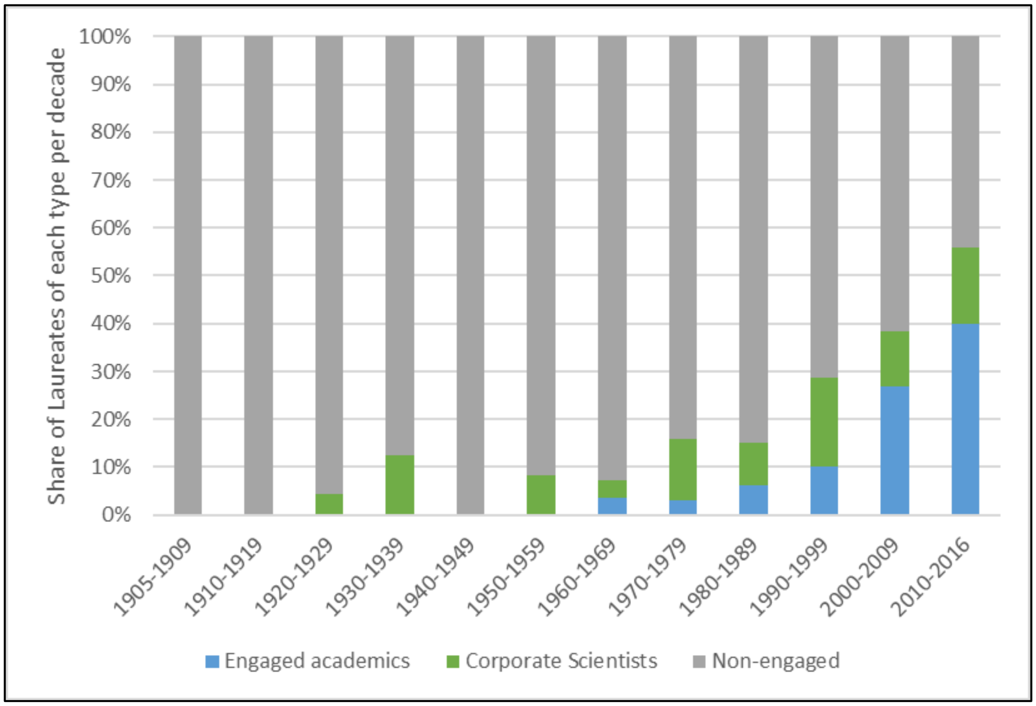

Figure 4 – Evolution of share of Nobel laureates interacting with the industry as engaged academics, corporate scientists or non-engaged, per decade and date of award

Hence, we demonstrated that **one-fifth of Nobel Prize** laureates in the sample were interacting with the industry. For the first time, during the last decades, more than 50% of laureates awarded in the 2010 – 2016 period were interacting with the industry at the time or before his/her breakthrough discovery. Our evidence also shows that while the share of corporate scientists has been staying stable since the 1970s, the number of engaged academics is highly increasing.

4. INDUSTRY INTERACTION EFFECTS ON NOBEL LAUREATES' ACADEMIC FOLLOW-ON RESEARCH

In this section, we compared the follow-on research performances and diffusion of research towards science and industry between the cohort of Nobel laureates that interacted with the industry in Period 0 and those who did not. To do so, we used a difference-in-difference model (D-i-D).

4.1. Variables and descriptive statistics

Our data set is a panel with two periods: period 0 and period 1 (**Figure 1**). When measuring academic performances and research orientations towards applied research while isolating the effect of interacting with the industry in Period 0, we need to hold for pre-existing differences between laureates in Period 0. It is consistent with previous findings on academic engagements that showed that engaged scientists have different individual characteristics (see Perkmann et al., 2013 for a review). Therefore, we used a Difference-in-Difference (D-i-D) model widely used in management science (e.g., Jung & Lee, 2014). The D-i-D variable is a dummy equal to 1 during the tested period (period 1) and for treated laureate only, and equal to 0 otherwise.

The variables definitions are reported in **Table 4**. Dependent Variables (DV) are the following: the *number of papers published by laureates;* the *number of papers published by laureates weighted by scholarly citations* to account for laureate work diffusion to industry; the *number of papers published by laureates weighted by SNPL citations* to account for laureate's research results diffusion to industry. We also explored the *number of patent families* published by laureates and the *number of patent families weighted by patent citations* to account for their performances of subsequent direct inventions. Finally, we also look at the *number of industry partners* to account for the laureate's effort to diffuse its research results with industry directly. Independent Variables (IV) are the following: *treated*, a dummy variable to account for the performances of the laureates that interacted with the industry; *period* a dummy variable to account for the difference between period 0 and period 1; *Difference-in-difference*, a dummy variable to account for the effect of having been inspired by industry in period 0 on tested DV in period 1. The *period duration* is used as an exposure variable to control differences between the available time to produce new academic papers and diffuse knowledge at each period. We also defined a set of control variables aligned with usual practices in the exploration of academic performances, including *born year* to control for changes in academic practices, *US-born laureates* to control if the laureate was born in the US, disciplinary characteristics (Chemistry, Physics, and Medicine), the age of the laureates at both its Prize paper and its Nobel award. We reported in **Table 5** descriptive statistics for all our variables.

Variable	**Definition**
Nbr. academic publications	Total number of academic papers published by the laureate in a given period.
Nbr. academic publications - Scholarly citations weighted	Total number of academic papers published by the laureate in a given period, weighted by the number of follow-on received academic citations.
Nbr. academic publications - SNPL citations weighted	Total number of academic papers published by the laureate in a given period, weighted by the number of follow-on citations of those papers in patents.
Nbr. patent families	Total number of patent families filled by the laureate in a given period.
Nbr. patent families - Patent citations weighted	Total number of patent families filled by the laureate in a given period weighted by the number of follow-on citations by other patents.
Nbr. industry partners	Total number of distinct indusrial company that interacted with the laureate in a given period.
Period	A dummy variable equal to 0 the period before the publication of the Nobel's paper of the laureate and 1 the period
Period duration	Count of the number of distinct years for a given period of the laureate.
Born year	Date of birth of the laureate.
US-born laureates	A dummy variable equal to 1 if the laureate is born in the US, 0 otherwise.
Female laureate	A dummy variable equal to 1 if the laureate is a female, 0 otherwise.
Chemistry Nobel	A dummy variable equal to 1 if the laureate was awarded with the Chemistry Nobel prize, 0 otherwise.
Medicine Nobel	A dummy variable equal to 1 if the laureate was awarded with the Medicine Nobel prize, 0 otherwise.
Physics Nobel	A dummy variable equal to 1 if the laureate was awarded with the Physics Nobel prize, 0 otherwise.
Age at Nobel's paper publication	The age of the Nobel laureate when he or she published the Nobel's paper.
Age at Nobel Prize winning	The age of the Nobel laureate when he or she was awarded with the Nobel prize.
Treated	A dummy variable equal to 1 if the laureate was industry-inspired before the publication of its Nobel's paper, 0 otherwise
Difference-in-difference	A dummy variable equal to 1 if the laureate was industry-inspired before the publication of its Nobel's paper and during the period after the publication of the Nobel's paper of the laureate and before being awarded with the Nobel prize (i.e. period 0).

Table 4 – Variable definition

Variable	**N**	**Mean**	**Std. Dev.**	**Min**	**Max**
Nbr. academic publications	1004	1.005	1.691	0	16.27
Nbr. academic publications - Scholarly citations weighted	1004	1.005	1.693	0	18.05
Nbr. academic publications - SNPL citations weighted	1004	1.005	3.240	0	34.16
Nbr. patent families	1004	1.003	7.660	0	146.65
Nbr. patent families - Patent citations weighted	1004	1.005	9.452	0	243.96
Nbr. industry partners	1004	1.002	2.992	0	42.94
Period	1004	0.484	0.500	0	1
Period duration	1004	15.113	10.823	1	57
Born year	1004	1919.169	23.121	1852	1974
US-born laureates	1004	0.375	0.484	0	1
Female laureate	1004	0.030	0.170	0	1
Chemistry Nobel	1004	0.300	0.458	0	1
Medicine Nobel	1004	0.357	0.479	0	1
Physics Nobel	1004	0.344	0.475	0	1
Age at Nobel's paper publication	1004	39.669	8.443	21	72
Age at Nobel Prize winning	1004	57.602	12.402	25	88
Treated	1004	0.214	0.410	0	1
Difference-in-difference (DiD)	1004	0.107	0.309	0	1

Table 5 – Descriptive statistics

4.2. Estimation

Formally, we used the following regression equation to estimate the effect of inspiration by the industry on the cohort of laureates, with Y_i a given Dependent Variable for laureate *I* and X_i a vector of controls variables:

$$Y_i = f(\beta_1 DiD_i + \beta_2 treated_i + \beta_3 period_i + \alpha X_i + \varepsilon_i)$$

Since the Dependence Variables of our models are a count of scores (non-negative integers), ranging from 0 to many, we used a Negative Binomial Regression (NBR) as a means of estimation and by controlling for period exposure (e.g., Baba, Shichijo, & Sedita, 2009; Zucker & Darby, 1996)[19]. As a standard requirement in panel data models, we used robust standard errors clustered by laureates. Then, the results of the estimation are reported in **Table 6**.

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[19] NBR is an extension of the standard Poisson model that succeeds in accommodating the overdispersion issue, then it is preferred to a standard Poisson Model that would assume that the variance of the counts is equal to the mean

	DV = Nbr. academic publications	DV = Nbr. academic publication - Scholarly citations weighted	DV = Nbr. academic publications - SNPL citations weighted	DV = Nbr. patent families	DV = Nbr. patent families - Patent citations weighted	DV = Nbr. industry partners
	(1-1)	(1-2)	(1-3)	(1-4)	(1-5)	(1-6)
Difference-in-difference treated vs. untreated (0/1)	**0.312*** (0.109)**	**0.660*** (0.133)**	**1.021*** (0.386)**	**-0.507 (0.438)**	**-1.765*** (0.546)**	**-16.26*** (0.205)**
Treatment	0.281*** (0.0966)	-0.211 (0.144)	-0.542* (0.309)	2.421*** (0.433)	3.634*** (0.711)	17.61*** (0.161)
Period	0.557*** (0.0576)	0.0833 (0.0801)	0.105 (0.352)	1.643*** (0.353)	3.084*** (0.369)	16.77*** (0.161)
Born year	0.0154*** (0.00173)	0.0331*** (0.00342)	0.0824*** (0.00530)	0.0509*** (0.00966)	0.0998*** (0.0156)	0.0350*** (0.00375)
US-born laureate	-0.210*** (0.0802)	-0.168* (0.0966)	-0.284 (0.264)	-0.192 (0.345)	-0.217 (0.359)	-0.318** (0.124)
Female laureate	-0.563*** (0.165)	-0.600*** (0.155)	-1.284*** (0.367)	-0.101 (0.942)	-1.316 (0.862)	-0.913** (0.377)
Chemistry Nobel	0.692*** (0.101)	0.290** (0.134)	1.564*** (0.272)	0.661* (0.362)	0.774 (0.490)	0.0534 (0.150)
Medicine Nobel	0.397*** (0.0994)	0.410*** (0.123)	1.955*** (0.342)	0.427 (0.382)	1.099* (0.563)	-0.129 (0.175)
Age at Nobel's paper pub.	0.00478 (0.00597)	0.00931 (0.00750)	0.0550*** (0.0145)	-0.00401 (0.0210)	0.0826*** (0.0239)	0.00369 (0.01000)
Age at Nobel Prize winning	-0.00154 (0.00373)	-0.0171*** (0.00496)	-0.0227* (0.0123)	0.0591*** (0.0165)	0.00768 (0.0206)	0.0102 (0.00695)
Constant	-33.23*** (3.371)	-66.15*** (6.573)	-164.3*** (9.813)	-107.3*** (18.94)	-204.1*** (30.87)	-87.89*** (7.382)
Exposure – time period	Yes	Yes	Yes	Yes	Yes	Yes
Log-pseudolikelihood	-1021.9801	-1121.1657	-913.46381	-623.8026	-480.60184	-845.77287
Wald chi-squared	468.46***	281.93***	482.11***	220.98***	211.84***	575.87***
Nbr. treated	108	108	108	108	108	108
Nbr. laureates	518	518	518	518	518	518
Observations	1,004	1,004	1,004	1,004	1,004	1,004

Robust errors clustered to laureate id in parentheses, * p<0.1, ** p<0.05, *** p<0.01

Table 6 – Negative Binomial Regression

Based on our regression, our D-i-D model showed that the effect of being inspired by the industry has a significant impact on the career trajectory of those Nobel Prize laureates. Hence, we showed that the direct effect of interacting with the industry in period 0 is that laureates publish more academic papers, with more academic impact and an increased level of diffusion to the industry than they would do without their industry relation. Furthermore, they also filled less impactful patents and had fewer industrial partners in period 1, than they would have had without being inspired by industry.

Nevertheless, our key objective is to compare those who interacted with the industry vs. other laureates in period 1. Then, we need to test if $\beta_1 + \beta_2 \neq 0$ which would mean that the industry's interaction in Period 0 would lead laureates to have different estimated mean for a given dependent variable. The results are presented in **Table 7**.

Chi-squared test: $\beta_1 + \beta_2 = 0$	DV = Nbr. Academic publications (1-1)	DV = Nbr. academic publication - Scholarly citations weighted (1-2)	DV = Nbr. academic publications - SNPL citations weighted (1-3)	DV = Nbr. patent families (1-4)	DV = Nbr. patent families - Patent citations weighted (1-5)	DV = Nbr. industry partners (1-6)
$\beta_1 + \beta_2$	0.593	0.449	0.480	1.914	1.869	1.346
Chi-squared	22.87	8.99	3.49	26.14	17.11	51.94
Prob > chi-squared	0.0000	0.0027	0.0618	0.0000	0.0000	0.0000
Status	**Reject**	**Reject**	**Accept**	**Reject**	**Reject**	**Reject**

Acceptance or rejection decision is based on a 5% confidence intervals ratio.

Table 7 – Mean difference test estimation of DV in period 1

First, we showed that laureates who interacted with the industry before or at the date of their Prize paper have a premium in the number of follow-on academic papers. On the one hand, they publish more articles in period 1 than they would have done without industry interaction and more papers than their peers. On the other hand, those results stand by considering the quality of the publications. Second, we showed that laureates who interacted with the industry have been prone to a more excellent orientation towards applied research than they would have done without being engaged with the industry in Period 0. Nevertheless, there are no significant differences between the orientations towards applications than their peers who were not interacting with the industry in period 0. Finally, models 1-4, 1-5, and 1-6 showed that the laureate who were not interacting with the industry in period 0 are catching up with those who do in terms of the number of patent families filled in period 1, associated impacts measured by patent citations, and the number of distinct industrial partners. Nevertheless, those who interacted in period 0 still get a premium regarding the rest of the cohorts in terms of direct industrial impact through patent filling and the number of their industry partners.

5. DISCUSSION

This research’s primary motivations were to explore the relation between scientists’ interactions with the industry and scientific breakthroughs, which ultimately shed light on the industry's role in the early emergence of new radical scientific knowledge.

To do so, we relied on the quasi-complete cohort of the Nobel Prize laureates in Physics, Chemistry, and Medicine, which conducted us to control for scientific breakthroughs that “*have conferred the greatest benefit to humankind*” (Alfred Nobel’s will, 1895). By (1) identifying the exact scientific paper that led them to be awarded the Nobel Prize and (2) by retrieving their ties with industrial companies based on their scientific papers and filed patents, we were able to specify those who interacted with the industry before or at the date of their prize paper. Then, we were able to monitor the magnitude and evolution of this phenomenon and compare the post-discovery behavior of laureates interacting with the industry with those who were not.

First, our contribution is to establish that despite the significant cut-off of corporate laboratories on fundamental research from the 1980s, the number of laureates interacting with the industry to be awarded the Nobel Prize is increasing. This phenomenon is mainly driven by the increase of engaged academics, while the share of corporate scientists awarded has remained stable since the 1970s. In the last observations period, the industry has contributed to more than one of two laureates for their breakthrough discoveries. We demonstrated that this phenomenon is discipline-dependent: more laureates are interacting with the industry in Physics and Chemistry than in medicine, even if we recently observed a catch-up phase. Finally, while The Bell Laboratories or IBM are well known for concentrating many Nobel laureates, many other industrial companies had influenced Nobel laureates. Second, we showed that despite that some Nobel laureates' scientific breakthroughs were partly made possible thanks to their industrial partners, the subsequent knowledge that they produced was not bound to their initial set of partners. Indeed, laureates interacting with the industry experienced similar knowledge diffusion-to-industry rates than other laureates, but higher academic production rates and diffusion-to-academia rates. We also show that interaction with industry does not lead to a more remarkable shift towards applied research than their Nobel laureates' peers.

Our study is subjected to several limitations. First, as highlighted in the methodological section, we explore the cohort of industry-inspired Nobel laureates for their breakthrough discoveries rather than testing the causal effect of academic engagement on the probability of making breakthrough discoveries. Testing this causal effect would require a counterfactual set of successful and unsuccessful scientific explorations conducted by interacting and not interacting with the industry scientists. Nevertheless, we were able to examine the extent to which scientists who made incredible breakthroughs were interacting with the industry and the evolution of this phenomenon through time. We hope that it will encourage scholars to collect more detailed and granular data to refine our findings and methods. Second, we assume that interaction with the industry prior (or at the date) to the Prize paper can be conceptualized as having a potential effect on the discovery. Nevertheless, one limitation is that we could not measure the magnitude of this effect as we are bind to a binary logic. The literature on academic engagement —mainly when using qualitative studies or survey methods —repeatedly showed that engaged scientists benefit from backward effects on their research quality by accessing diverse original knowledge building blocks, different ways of thinking, fruitful synergies with industrial companies' activities, etc. Based on that observation, their ties with the industry through patents and publications before the breakthroughs, and the magnitude of the breakthrough to be awarded the Nobel Prize, we considered our approach constituted a robust proxy of the industry inspiration. In-depth qualitative studies based on more detailed data could better understand those mechanisms. Third, ties with the industry could have been underestimated. One reason is that it is possible that for competitive reasons, a given industrial company refuses to appear in the authors' affiliation organizations of scientific papers. Another reason is that other types of ties may be included. Further studies could explore additional ties by reviewing companies established by Nobel laureates, Nobel laureates participating in Board of Directors or as advisors for industrial companies as well as more informal relations with the industry (former Ph.D. students that went to the industry, invitations to companies' events, involvement in contract research that did not end up with either patents or publications, etc.). Four, we created an original database by using very conservative assumptions that limit type-2 errors. The exception concerns patent assignment to Nobel laureates—one of the most challenging tasks in our study—as we may have included in the dataset patents that were filled by someone who would have similar first name and surname, who worked with the same company, or institution than the laureate, in a similar period of activity than Nobel laureates. We consider here this risk as limited for our study purposes. Our conservative approach may also be subjected to type-1 errors as we may have rejected proper industrial ties that were not consistent (misspelling issues, for example). Five, a bias in the sample could be that the Nobel committee would give the award to scientists more oriented towards basic science than applied sciences. Nevertheless, this bias seems limited as Alfred Nobel's will specify that the award can be granted to both scientists and inventors, which can be viewed as an orientation towards basic and applied research[20].

Our findings contribute to the literature on academic engagement. We acknowledge that the need to explore the relation between academic engagement and scientific breakthroughs was clearly defined in the research agenda designed by Perkmann et al. (2021). While it was previously shown that academic engagement is widely practiced across all disciplines (Cohen, Nelson, & Walsh, 2002; Hughes et al., 2016), we bring evidence that (1) it constitutes a reality also for the most incredible scientific advances in modern science and (2) academic engagement is becoming more and more practiced by scientists who made major scientific breakthroughs. Our results regarding the comparison of academic performances and post-Prize Paper behaviors between laureates interacting with the industry and the others complement previous literature findings. Hence, first, we noticed that they published a higher number of articles in period 0 than their peers,

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[20] "*one part to the person who made the most important discovery or invention in the field of physics; one part to the person who made the most important chemical discovery or improvement; one part to the person who made the most important discovery within the domain of physiology or medicine*" (Alfred Nobel's Will, 1895).

which echoes the finding that academics with more publications are more prone to be engaged with the industry (e.g., Gulbrandsen & Smeby, 2005; Tartari, Perkmann, & Salter, 2014). We also found that laureates interacting with the industry published more follow-on papers than their peers, even when considering the quality of those publications. It matches with a robust line of works claiming that one consequence of academic engagement is an increase in the number of publications (e.g. Blumenthal et al., 1996; Gulbrandsen & Smeby, 2005; Hottenrott & Lawson, 2017). The quality of those publications remained unclear, but our finding showed that for star scientists it has a positive effect, which is aligned with Bikard et al. (2019) and Hottenrott & Lawson's (2017) findings on non-star scientists. Finally, we also contributed to the literature by demonstrating that laureates interacting with the industry did not have a more excellent orientation towards applied research than their non-industry-inspired peers. It seems that those Nobel laureates were able to maintain their orientation towards basic research by continuously being engaged with their industrial partners, including for commercialization activities measured through filled patents or for collaborative research projects (co-publications).

Our findings also contributed to a broader literature on the industry's role in science. It has been repeatedly shown that the industry focused more, at least since the 1980s’, on knowledge absorption than knowledge creation (e.g., Arora et al., 2018). While large corporate laboratories such as the Bell Laboratories or IBM and all their Nobel alumni are usually presented as a gone “*golden age*” (Gertner, 2012) of industrial research, our findings showed that the contribution of the industry to modern scientific discoveries remains essential in their ability to influence or inspire scientists. The key actors of this “*golden age*” such as 1956 Nobel laureates William Shockley, Walter Brattain, and John Bardeen at the Bell Laboratories or even 1920 Nobel laureate Charles-Edouard Guillaume were “*unusual*” (Cahn, 2005: 145) at that time as the share of laureates interacting with the industry was limited before the 1990s. Hence, it advocates for a renewal of the understanding of university-industry interactions and research activities pursued in industrial contexts as the magnitude of this phenomenon might have been undervalued. Scientists interact with the industry in complex ways that go far beyond transfer. Rather than being science supplier for the industry, some scientists are involved in relationships with industrial corporations that favor radical new scientific knowledge development. Instead of hurting academia through barriers to sharing and publications (e.g. Murray, 2010), the industrial partners of Nobel laureates could not fully capture the value of those critical scientific breakthroughs and favor those discoveries. It echoes Bikard et al. (2019) observation that industry and academia's institutional environments are complements rather than substitutes. It opens rooms for further research to better understand how the industry benefited from their relationships with engaged and corporate scientists.

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