Effects of interdisciplinarity on disciplines: a study of nanomedicine in France and California

Séverine Louvel

Séverine LOUVEL

Effects of interdisciplinarity on disciplines: a study of nanomedicine in France and California[1]

Also Published as: Louvel, S. « Ce que l'interdisciplinarité fait aux disciplines: une enquête sur la nanomédecine en France et en Californie ». *Revue Française de Sociologie*, 56(1), 69-97. doi:10.3917/rfs.561.0075.

Annual English Selection of the *French Journal of Sociology*
Cairn international edition https://www.cairn-int.info/article-E_RFS_561_0075--effects-of-interdisciplinarity-on-discip.htm

Abstract
The rise of interdisciplinarity in the sciences raises many questions about the future of the disciplines as such. To what degree will they remain the main units for differentiating between the sciences? Are disciplines destined to disappear or rather to combine in new ways in response to scientific dynamics and political pressures in favor of interdisciplinarity? The article studies the effects of interdisciplinary cooperation on disciplinary territories and boundaries. Rather than emphasizing the cognitive dimensions of disciplines, an approach frequently applied in the sociology of science, I focus on their social dimensions; specifically, the extent to which interdisciplinarity can be a resource for action and help existing disciplines consolidate their institutions. Empirical study of nanomedicine in France and California brings to light two features that work to bolster the territories of disciplines whose practitioners engage in interdisciplinarity: one, interdisciplinary practices that help to demarcate the given discipline from earlier or competing approaches; two, discipline boundary flexibility, which can work to promote discipline jurisdiction extension.

Keywords: Public research — Scientific disciplines — Interdisciplinarity — Disciplinary program — Science policy — Nanomedicine

Interdisciplinarity raises several questions about the future of the academic disciplines. Defined as "a way of fitting together bodies of knowledge that leads to ongoing partial reorganization of existing theoretical fields, as if through dialogue" (Béchillon 1997: 186),[2] interdisciplinarity has become increasingly commonplace in recent decades due to developments in both public policy and scientific dynamics. Since the late 1960s, not only

[1] My thanks to the anonymous reviewers of the *Revue Française de Sociologie* editorial committee for their extremely helpful criticisms of earlier versions of this article. The text also benefited from the judicious comments of several colleagues, among them Béatrice Milard, Matthieu Hubert, Thomas Reverdy and Vincent Mangematin. Lastly, let me thank the French National Research Agency (ANR) for funding this study as part of the ANR 2010 Blanc project - 1811-01.

[2] Other authors offer similar definitions of interdisciplinarity (Vinck 2000; Weingart and Stehr 2000), distinguishing it from both multidisciplinarity (a juxtaposition of bodies of knowledge that leaves disciplines intact) and cross-disciplinarity (the integration of several disciplines).

governments but also the OECD, followed by the European Union, have brandished interdisciplinarity as a tool for combating academicism in public research (Weingart and Stehr 2000) and promoting the socio-economic benefits that can follow from such research. This policy discourse, which stresses the importance of innovation (Barry, Born and Weszkalnys 2008), came to a head in the 1990s with a call for the generalization of a knowledge production mode dubbed "mode 2": knowledge production would no longer be structured around predefined disciplines but rather problems to be solved such as climate change, finding a cure for cancer, etc. (Gibbons et al. 1994). Moreover, interdisciplinarity is understood to develop by way of "ontological logic" (Barry, Born and Weszkalnys 2008) and in response to dynamics internal to the sciences (Lenoir 1997; Dogan and Pahre 1991; Bonaccorsi 2010).

Is interdisciplinarity putting an end to academic disciplines? The idea of dissolving disciplinary boundaries through "mode 2" knowledge production has been criticized for being irrealistic and lacking socio-historical grounding (Godin and Gingras 2000; Weingart and Stehr 2000; Shinn and Ragouet 2005). However, the particular ways in which interdisciplinarity works to transform disciplines, the latter defined as the essential units in organizing and differentiating contemporary sciences (Dubois 2014),[3] have not yet been fully explored. The question is interesting for sociologists in two respects. First, it fuels a long-established tradition of research on the emergence and development of scientific specialties and disciplines (Lemaine et al. 1976) that is in turn linked to a fundamental debate in the sociology of science on the respective roles of endogenous and exogenous dynamics in institutionalizing sciences (Shinn and Ragouet 2005). Second, it is a means of taking a position in the debate around contemporary attacks against scientific community independence. Up against the political claim that interdisciplinarity contributes to the economy of knowledge, some disciplines feel besieged, not to say sacrificed.[4] Analyzing disciplinary reconfiguration will enable us to probe the equation between a policy watchword and priority: interdisciplinarity; the weakened ability of disciplines to circumscribe legitimate bodies of knowledge; and the instrumentalization of scientific knowledge.

The effects of interdisciplinarity on disciplinary territories and boundaries are explored here through the case of nanomedicine, i.e., the use of nanotechnology in medicine. Nanomedicine is particularly well adapted to this type of study, for two reasons. First, there is disagreement around nanotechnology between, on the one hand, institutional promoters, who predict "NBIC

---

[3] There are several definitions of the term discipline: "the notion of discipline enjoys popular approval but not the approval of dictionary writers … the vast number of terms used to explain it comes close to being incommensurable" (Blanckaert 2006: 136). Specifically, authors differ on the importance they attribute to the cognitive and social dimensions of disciplines. The cognitive dimension is a stock of cognitive and instrumental resources shared by a delimited set of researchers (Fabiani 2006). The social dimension corresponds to the institutions that establish the discipline as "an independent system entertaining particular relations with the world outside science—i.e., technology, industry, policymaking and education—that enable it to procure resources and to interest an audience in its accomplishments" (Stichweh 1994: 56). For one set of authors, disciplines (in contrast to specialties) have no cognitive substance (Cambrosio and Keating 1983); they also claim that intradisciplinary differences are sometimes greater than interdisciplinary ones (Barry, Born and Weszkalnys 2008; Dogan and Pahre 1991). For others, the importance of the cognitive dimension varies by discipline (Whitley 1976).
[4] This discourse circulates in the humanities and social sciences, among others (Conesa et al. 2013).

(Nanotechnology, Biology, Information and Communication Technologies) convergence" (Roco and Bainbridge 2002), and on the other sociologists of science who have endeavored to demonstrate the weight of existing disciplines in scientific practices (Schummer 2004; Rafols and Meyer 2007; Marcovich and Shinn 2011). Second, interdisciplinarity has developed as a combined effect of scientific and policy logic, meaning that it is necessary to circulate between different analytical levels: laboratories, departments, funding agencies, journals, etc. From a science perspective, nanotechnology has contributed "molecular tools and molecular knowledge of the human body" to biomedical research (European Science Foundation 2004)[5] and represent a new stage in molecular-scale analysis (Gaudillière 2002). And like molecular biology, created by physicists in the 1940s (Morange 1994), nanomedicine is based on intense exchange between biologists and researchers in the chemical, physical and engineering sciences (physical chemistry, chemistry, biophysics, electronics, computer science, signal processing, etc.). From a policy perspective, institutional actors see interdisciplinarity as absolutely necessary to achieving the potential of biomedicine, particularly the market potential promised by nanotechnology and other areas of biomedical research (Brunet and Dubois 2012).[6]

In contrast to contemporary analyses of interdisciplinarity in the sciences, I emphasize social changes in disciplines that play a role in nanomedicine. Specifically, I will be asking to what degree interdisciplinarity can benefit "disciplinary programs," defined as actions for consolidating discipline-based institutions (Lenoir 1997; Dubois 2014).

The first section reviews the sociology of science literature on the impact of interdisciplinarity on disciplines. I show that most of that literature is sociology of scientific work focused on the cognitive dimensions of disciplines, and suggest the usefulness of shifting the focus to links between interdisciplinarity and discipline-related institutions such as journals. In the second section I draw on a study conducted in France and the United States to identify the practices and ambitions characteristic of interdisciplinarity in nanomedicine. I show that there is currently no "disciplinary stake" in this area; in other words, no interest in bringing scientific practices into existence in the form of a new discipline (Cambrosio and Keating 1983: 328); this is consistent with the concern to valorize nanomedicine within the respondent's own specialty. In the third and last section I show how interdisciplinarity serves the disciplinary program**s** of the chemical, physical and engineering sciences (Lenoir 1997: 55). First, interdisciplinary practices are particularly useful in the "boundary work" (Gieryn 1983) by which these specialties distinguish their approach from competing ones in the life sciences. Because researchers in the chemical, physical and engineering sciences appear to possess indispensable skills, they have a relatively strong position in training programs and the academic job market. Second, the plasticity or flexibility of these disciplines (Bensaude-Vincent 2001: Bensaude-Vincent and Stengers 2001; Ramunni 1995) makes it relatively easy

[5] Despite the fact that research in disciplines like biology and chemistry has been done at the molecular scale for decades already (Webster 2006), there is consensus on the wide range of biomedical possibilities opened by nanotechnology.
[6] See Box 1 on the study I conducted in France and California of the main institutional supporters of nanomedicine in France and the United States.

for them to extend their jurisdiction to the study of living things (Abbott 1988). This in turn has two effects: those disciplines integrate and legitimate the study of living things in their own disciplinary instruments, particularly their journals; they enjoy increased funding opportunities and are particularly capable of meeting public research demands for innovation.

Interdisciplinarity and discipline boundaries: multiplication, dissolution or reconfiguration?

Researchers in history and sociology of the sciences have long studied links between interdisciplinarity and discipline dynamics, specifically to determine how those dynamics develop. Interdisciplinary exchanges play a significant role in historical processes of discipline differentiation and segmentation (Dogan and Pahre 1991).[7] There is disagreement among these studies about the relative roles of intellectual exchanges, professional interests and institutional clout in the emergence of specialties and disciplines. Two now classic studies stand directly opposed on this point. Nicholas Mullins (1972) claimed that intellectual and social activities (development of research styles, a change in communication and sociability structures, student training) played a major role in the creation of molecular biology. In this he was explicitly countering the argument of Joseph Ben-David and Randall Collins (1966) that experimental psychology had risen on the foundation of the professional structure of the parent disciplines (physiology and philosophy) in connection with their relative statuses and associated career opportunities.

The position of the disciplines in interdisciplinary scientific work

Alongside what is still an active research tradition in the history of science, there has been a set of studies that focus on interdisciplinarity as the main force behind discipline boundary redefinition. These studies are generally based on ethnographic analyses of scientific work and focus on research groups whose borders do not correspond to disciplinary ones: "invisible colleges" (Crane 1972), "transepistemic arenas" (Knorr-Cetina 1982), "scientific cooperation networks" (Vinck 1999), "research technologies" (Joerges and Shinn 2001), "research ensembles" (Hackett et al. 2004), "hybrid institutionalized or informal collectives" (Dogan and Pahre 1991). The preferred analytic unit in them is the research project, understood as the scale at which "arrangements of materials, techniques, instruments, ideas and enabling theories"(Hackett et al. 2004)—i.e., different ways of engaging in interdisciplinarity—operate. In this understanding, there are at least two explanations for the weakening of disciplinary boundaries: narrow specialization in contemporary sciences fragments the disciplines, which in turn leads to hybridization of the resulting science fragments (Dogan and Pahre 1991); the advent of reductive approaches in several scientific areas—that is, studying complex systems by studying their simple components—has made interdisciplinarity crucial when it comes to integrating other analytic levels (Lenoir 1997; Bonaccorsi 2010).

[7] Here we can cite molecular biology (Mullins 1972); biochemistry and molecular biology (Gaudillière 2002); psychology (Ben-David and Collins 1966); bioinformatics (November 2012); materials science (Bensaude-Vincent 2001); immunology (Löwy 1990); solid-state chemistry (Teissier 2010), etc.

While these authors are attentive to interdisciplinary exchange, they do not reject out of hand or attempt to argue away the need for specialty and discipline boundaries in scientific practice. Star and Griesemer (1989) developed the notion of boundary object to show that material circulating in interdisciplinary networks allows for cooperation between social worlds that nonetheless remain clearly delimited by particular stances, identities, issues or stakes (Trompette and Vinck 2009). Similarly, other authors have described cooperation among disciplines or scientific communities as "trading zones" (Galison 1997), "interstitial arenas" (Joerges and Shinn 2001) or "borderlands" (Marcovich and Shinn 2011) that belong to none of the given groups and do not represent a threat to scientific identities. Lastly, some studies emphasize the importance of disciplinary references in interdisciplinary projects, the point being to criticize the project of generalizing "mode 2" scientific production (Gibbons et al. 1994). Up against an "anti-differentiation" front calling for the dissolution of disciplinary boundaries (and more generally, of academic science boundaries altogether), the authors of these studies see the sciences as sharply different from each other and separated by boundaries (Shinn and Ragouet 2005; Brunet and Dubois 2012) and insist on scientific communities' relative autonomy from the economic and political fields as well as the concomitance of dynamics of disciplinary differentiation and convergence, convergence due in particular to instrument circulation (Shinn and Ragouet 2005: 145). Along the same lines, Anne Marcovich and Terry Shinn (2011) have developed the concept of "new disciplinarity" to describe the place of the disciplinary regime (Shinn 2000) in interdisciplinary nanoscience research.[8] Disciplines provide researchers with specific vocabularies, relevant questions and communication resources. Scientists' centrifugal and centripetal movements vis a vis their disciplines do not erase the boundaries of those disciplines: "Displacement refers to a selective intermittent movement of a scientist into the borderland of his discipline […]. The discipline constitutes the referent and acts as a constant, attractive, gravitation-like force on the practitioner" (Marcovich and Shinn 2011: 596).

Taken together, these studies conclude that while research groups working collectively on scientific projects are often interdisciplinary, interdisciplinarity does not abolish disciplinary references or territories. Stressing the cognitive dimensions of disciplines, these studies do not examine how interdisciplinarity changes discipline-related institutions such as journals. Either they omit this question implicitly from the scope of their study or they explain that discipline-related institutions are relatively inert and therefore have little to tell us of interdisciplinary practice dynamics.

Why analyze the impact of interdisciplinarity on discipline-related institutions

My purpose here is to analyze relations between interdisciplinary research and the redefining of discipline territories in terms of their social, professional and institutional dimensions. The assumption here is that disciplines are an instrument of collective action for scientists (Vinck

[8] Schummer 2004 and Rafols and Meyer 2007 seek to identify indicators of the role of disciplines in scientific practices and publications in nanoscience.

2000: 72), and on this basis I study the degree to which interdisciplinarity can in fact serve "disciplinary programs" and therefore help protect discipline boundaries and extend discipline territories. Here I am following Timothy Lenoir and other authors after him (Dubois 2014), who use the term "disciplinary programs" to designate the actions by means of which disciplines become "political institutions that demarcate areas of academic territory, allocate privileges and responsibilities of expertise, and structure claims on resources" (Lenoir 1997: 58). In this understanding, the success of disciplinary programs follows not from scientific success but rather an ability to generate institutional niches that will host scientific approaches and provide resources for "organizing employment, establishing service roles, creating reward systems and routinizing professional socialization" (ibid.). Michel Dubois has identified five actions that reinforce disciplinary programs as defined by George Sarton and Robert K. Merton: having as much weight as possible on the academic job market; demarcating the given discipline from preexisting or surrounding ones; creating and running disciplinary instruments (journals, associations, laboratories); training and transmitting a scientific ethos to disciples and getting them hired; producing a narrative of disciplinary identity. The notion of disciplinary program partakes of a vision of science as agonistic and competitive, a vision in which the discipline is the means to obtain scarce resources for and lasting institutionalization of research programs.[9] However, in that vision the discipline is not a purely social entity or mere rhetoric developed in connection with power issues, but rather a scientific, technical, social and organizational construction (Lenoir 1997: 61) consolidated by the disciplinary program.

Presented as an eminently collaborative field that will, as such, bring into existence a "new biology" (National Research Council 2009), nanomedicine offers a particularly interesting ground for observing interdisciplinarity. In the following section I characterize it in terms of its disciplinary composition and the interdisciplinary practices and ambitions to be found in it. I show that scientists have no desire for it to be a discipline but instead work to integrate nanoscience and nanotechnology into their own specialties. Given the absence of a disciplinary stake in nanomedicine, I examine the social reasons for the fact that chemical, physical and engineering science specialties are particularly numerous in this area and are growing in proportion to others. In the last section I show how interdisciplinarity can in fact serve the disciplinary programs of those scientific specialties. First, interdisciplinarity is useful to those specialties when it comes to demarcating (Gieryn 1983) them from the life sciences, a move that makes them appear indispensable to the development of the field and affords them an extremely favorable position in training programs and the academic job market. Second, those specialties have a degree of plasticity or flexibility that makes it relatively easy for them to integrate living things into the objects they investigate. Extending their jurisdiction in this way facilitates the valorization of nanomedicine in their own disciplinary instruments (journals in particular) and enables them to vary and multiply their funding sources.

[9] Lenoir (1997) explicitly identifies this as part of Bourdieu's program for analyzing scientific fields (Bourdieu 1984).

Box 1. — ***A qualitative study of nanomedicine in France and California***

This article draws on a qualitative study conducted in France and California in 2011-2012. The empirical material consists of 62 recorded and fully transcribed face-to-face interviews with nanomedicine researchers (37 in France; 25 in four Universities of California: Berkeley, Davis, San Francisco and Santa Barbara);[10] analyses of documents (outlook reports, policy statements, etc.); bibliometric analysis (publications referenced in the Web of Science)[11] and analysis of project databases.

France and the United States: contrasting interdisciplinary research situations

The survey was part of a project on the dynamics of structuring nanomedicine as an interdisciplinary research field.[12] It combines sociology of science and sociology of public policy on science and innovation, and it examines the respective weights of scientific concerns on the one hand, institutional pressures in favor of interdisciplinarity on the other. This focus explains my choice of two countries that could be assumed to exhibit quite different institutional conditions for the development of interdisciplinarity: France, whose academic structures are generally considered unfavorable to interdisciplinarity (discipline-based career management by national authorities, institutional separation at the *département*, university or research institute scale), and the United States, often cited as an example of a university system that facilitates interdisciplinary research.

The contrast between France and the United States when it comes to supporting interdisciplinary research is particularly clear for the life sciences. Several references to the "American model" may be found in French reports on the subject (MINEFI 2011; OPECST 2004). The model is associated with the American university system (decentralization, which facilitates action by institutional entrepreneurs seeking to break down disciplinary boundaries;[13] heavy competition for reputation, which leads to risk-taking and stimulates intellectual pluralism [Whitley 2003]); and scientific policy (it is relatively easy in the US to raise funds quickly for emerging interdisciplinary science fields [Bonaccorsi 2007]). Since the 1980s in the US there have been several far-reaching initiatives to develop fields that will work as interfaces between the life sciences and physics and the engineering sciences: genetic engineering in the 1980s; bioengineering and bioinformatics in the 1990s (Agnew 1998). In the 2000s, two types of National Institutes of Health (NIH) grants in nanomedicine became

[10] Interviews conducted while I was a Visiting Scholar at UC Berkeley's Center for the Study of Science, Medicine and Society (Spring 2012).

[11] Run by Thomson Reuters, the Web of Science is the largest bibliographical database available, with over 10,000 journals.

[12] Project funded by the ANR [French National Research Agency] under the title *Hybridtrajectories* (ANR 2010 Blanc-1811-01).

[13] The kind of entrepreneurial dynamism that drove the creation of molecular biology departments in the 1980s (Jong 2008).

available,[14] one for setting up Nanomedicine Development Centers (NDCs) (8 centers created since 2004), the other for the "Alliance for Nanotechnology in Cancer" (8 centers of excellence, 12 partnership platforms and 11 interdisciplinary teaching and research teams created from 2005 to 2010 by the NIH National Cancer Institute). The lag in this area in France (and Europe) has been attributed to institutional and disciplinary dividing walls and a lower level of political voluntarism: less substantial and less well organized public funding, lag in understanding the technological, economic and clinical stakes involved in bioengineering (OPECST 2004), no funding earmarked for nanomedicine (European Science Foundation 2004). National agencies and the European Commission are working to catch up by funding research grants in nanomedicine.[15]

Choice of survey population
The US interviews were conducted within the geographical area of California's "Biotech Bay," often considered a model for biotechnology development and therefore likely to have a concentration of nanomedicine research. No particular region in France was circumscribed prior to the survey.

The survey population was chosen from among scientists in charge of publicly funded research projects (NIH and ANR specific topic research grants). Care was taken to cover the three main research avenues in nanomedicine (drugs, medical devices, and regenerative medicine, the last of these being not as heavily represented as the other two in nanomedicine generally and my survey population in particular)[16] and to include diverse therapeutic applications (cancer, cardiovascular and neurodegenerative diseases).

Nanomedicine, a bioengineering field

The practices and aims of interdisciplinary work in nanomedicine

Nanomedicine is part of bioengineering, a discipline that "integrates physical, chemical or mathematical sciences and engineering principles for the study of biology, medicine, behavior or health."[17] The intense exchange between biology specialties (biochemistry, molecular biology, cellular biology, bioinformatics) and specialties that make, observe or describe

[14] Both are part of the National Nanotechnology Initiative (NNI), a federal policy in support of nanotechnology launched in 2000 with a combined budget of $21 billion in 2014 (source: http://www.nano.gov/about-nni/what/funding).
[15] France's ANR has three nanomedicine-related funding programs: *Nanotechnology and nanosystems* (P2N), *Techsanté* and *Nanobio*. At the European Union scale, nanomedicine research is primarily funded by the relatively broad Health and NMP programs (covering nanoscience, nanotechnology, new materials and production technologies) (Sixth EU Framework Programme and first four calls for proposals of the Seventh Framework Programme)...
[16] Most overviews of nanomedicine note the overrepresentation of the first two fields; see the Bionest Partners report (2008).
[17] The NIH working definition (2007) http://www.becon.nih.gov/bioengineering_definition.htm, often cited in French CNRS outlook reports. In addition to nanomedicine, bioengineering comprises synthetic biology, stem cell research and tissue engineering.

nanometric objects (chemistry, applied physics, mechanical science, electronics, bioinformatics, materials science and/or signal processing, depending on the project) is meant to enrich our knowledge and ability to act on living things. Nanomedicine has grown extraordinarily in recent years, as attested by the exponential rise in publications in the field (185,074 articles referenced on the Web of Science in June 2014 as against approximately 20,000 in 2004).[18]

The notion of interdisciplinarity covers such a wide range of different scientific techniques (Dogan and Pahre 1991) that in order to analyze the role and weight of the various disciplines in them it is important to identify interdisciplinary nanomedicine practices. There are two interdisciplinarity operating modes in nanomedicine (Vinck 2000): complementarity (between the discipline-related skills of the various researchers working together to attain a common analytic or conceptual goal) and importation (concept, method or model-borrowing). The two modes are found to operate in all projects, though they do not have equal importance. First, interdisciplinary practices in nanomedicine are based on complementarity between the observation and measuring instruments used in the chemical, physical and engineering sciences on one hand, in the life sciences on the other. Those practices are central to nanomedicine projects aimed at improving our understanding of living things and diagnosing dysfunctions. Biophysics, chemistry and bioinformatics tools are means of acquiring better knowledge of molecular mechanisms (in the *Protein folding* project, for example, they enable researchers to identify individual molecules and cells in complex biological environments; see Box 2 below and *ETP Nanomedicine* 2005: 16) and improving diagnostic instruments (*Optic imaging* project; see Box 2). For example, in vitro diagnostic techniques using magnetic nanoparticles are ten million times more sensitive than conventional molecular biology techniques (Mirkin, Nel and Thaxton 2011: 232).

Box 2 — ***Interdisciplinarity as complementarity between observation and measurement instruments***

***Optic imaging* project**

This project uses fluorescent nanoparticles as a contrast agent in optic imaging. The head of the research unit is a **physical chemist.** Funded by the French National Research Agency, the project began with a dissertation in **polymer chemistry** on synthesizing a nanoparticle. During the thesis work the supervisor developed collaborative projects with **chemists** and **physical chemists,** who contributed nanoparticle **characterization** tools, and a **biologist** and an **immunologist** who studied **the particle's** immune-toxicity on animal models. Their work was published in the *Journal of Biomedical Nanotechnology*.

***Protein folding* project**

[18] Web of Science consulted June 17, 2014; see Appendix, Box A1 for consultation method. The rise is explained not only by growth of the field but also by editorial opportunism and as a branding strategy: over 160 nanotechnology journals were founded in the 1990s (Grieneisen 2010).

Funded as a Nanomedicine Development Center project by the NIH, this project brought together approximately ten teams studying and designing proteins that would facilitate protein folding (poor protein folding being the cause of several diseases). The project developed around complementary studies for characterizing these "chaperone" proteins: functional studies, involving collaboration between **chemists** and **biochemists**; and structural and mechanical studies, involving collaboration between **biophysicists** and **structural biologists**. **Bioinformaticians** then used this knowledge to simulate protein dynamics and interactions. Simulation in turn enabled researchers to synthesize the chaperone proteins (by way of **bioinformatics** and **mechanical engineering**), which were then characterized using biophysics, chemistry and biochemistry tools. The work was published in the journal *Nature Nano.*

Second, interdisciplinarity involves method and model importation. This type of interdisciplinary practice is particularly important in projects where researchers are fabricating an object with certain biological properties and functions (a nanostructured membrane in the *Tissue regeneration* project, and nanocarriers or nanovectors delivering drugs to targets in the *Nanodrug* project; see Box 3). Chemists and materials science researchers contribute know-how acquired when working in other areas (energy, the food industry, microelectronics, etc.) and use it to improve molecular and cellular biology synthesizing techniques—in cellular therapies, for example (*Tissue regeneration* project; Mirkin, Nel and Thaxton 2011: 252). Furthermore, in the *Protein folding* project, researchers in the engineering sciences (or mechanical engineering) imported general or reverse engineering[19] methods and principles when synthesizing "chaperone" proteins. Such contributions are also central to some tissue engineering projects: "we develop new strategies for assembling nano fibers and minerals in a structure. We mimic the natural structure of bones using a bottom-up approach" (California, Interview 6, chemist).

Box 3 — ***Interdisciplinarity as method and model importation***

***Tissue regeneration* project**
Funded by the French National Research Agency, this project uses nanotechnology to fabricate "bioactive" or "intelligent" implants that only release the active substance upon contact with the cell, thereby improving stem cell-driven tissue regeneration. The project head is a **biochemist.** She works with **polymer chemists,** who are fabricating the nanostructured membrane on which the stem cells multiply. She also works with **cellular biologists,** who generate stem cells (iPS cells) and perform in vitro and in vivo tests. Their work has been published in the *American Chemical Society Nano (ACS Nano).*

***Nanodrug* project**

[19] Reverse engineering is the work of designing objects inspired by biological structures present in nature. It is considerably important in tissue engineering.

Funded by an NIH R01 grant for investigator-initiated projects, this project uses the targeting capacity of nanoparticles to better administer drugs. The project head is a **pharmaceutical science** researcher. She is working with a **chemical engineering** professor who designs and makes nanoparticles for medical use or energy applications. The team's competencies in **pharmaceutical sciences** enable it to help develop drugs (excipients, etc.) and in **biology**, to study drug effectiveness and biocompatibility on animals. Its work has been published in the *European Journal of Pharmaceutics and Biopharmaceutics.*

Altogether, these interdisciplinary practices serve doubly instrumental epistemic aims. At one level, they contribute knowledge acquisition and action modes that fuel biomedical innovations. In a way, knowledge of living things is not so much an objective in itself here as a means of creating "predictive, personalized, preemptive and participatory medicine" (the NIH's "4 P's") based on molecular information rather than empirical and symptom knowledge. At another level, this kind of interdisciplinarity is a continuation of the twentieth-century philosophical project of using several disciplines at once to control and manipulate life (Calvert and Fujimora 2011). This instrumental understanding is particular strong among researchers who say that nanomedicine is part of synthetic biology and that the world can be changed prior to knowing it.[20]

Interdisciplinarity with no disciplinary stake

Nanomedicine researchers all engage in interdisciplinary practices and use them in the service of a shared instrumental vision. Goal-sharing of this sort leads them to plead in favor of interdisciplinary program funding but not to formulate any "disciplinary stake" (Cambrosio and Keating 1983) or defend a "disciplinary program" for nanomedicine (Lenoir 1997).[21] These researchers identify with their specialty and think of the nanotechnology as tools that enrich it. Moreover, the low number of discipline-specific instruments (journals,[22] laboratories, academic departments or training programs) attests to the fact that professional closure or institutional niche occupation strategies are marginal. Conversely, nanomedicine appears a label to be defended in the interest of extending one's own field: "Speaking about nanomedicine has more value for funding agencies to acknowledge that there are new perspectives from physicists, from engineers that could be useful in addressing health care problems. The real impact is bringing new people who woudn't be working on medicine or clinical therapies, bringing their viewpoint in" (California, Interview 8, bioengineer).

[20] This applies to *Protein folding* project researchers. Moreover, in presenting his research team, a cellular biology researcher I interviewed cited a laureat of the 1965 Nobel Prize for Physics Richard Feynman: "What I cannot create, I cannot understand" (California, Interview 11).

[21] However, disciplinarization processes (which depend less on the scientific coherence of a field than on actions by scientists and their sponsors) may well get underway in the future, as has happened in the United States with biomedical engineering, made into a discipline in the 1990s and 2000s when the Whitaker Foundation decided to fund the 80 university departments in it.

[22] There is only one nanomedicine "department" in the United States (the country with the greatest concentration of nanomedicine research) and France has only three nanomedicine "laboratories." Furthermore, the two journals explicitly dedicated to nanomedicine (*International Journal of Nanomedicine*, ranked in the nanoscience-nanotechnology and pharmacy-pharmacology categories, and *Nanomedicine*, identified as biotechnology-applied microbiology and nanoscience-nanotechnology) are not among the main nanomedicine publications.

A field "populated by engineers and physicists"

The practice of interdisciplinarity goes together with a particular division of labor between "new entrants" in biomedical research, who work primarily on organic and/or manmade objects, and the field's more traditional actors. To schematize, researchers in the chemical, physical and engineering sciences import instruments, models and principles into nanomedicine and are therefore logically active in project design, fabrication and testing stages, while biologists assume the indispensable but more tightly circumscribed role of data providers. Situated "upstream" of "rational" biological object synthesis, biologists contribute their knowledge of the properties and action modes of natural molecules, precisely those molecules that the synthesized object will reproduce (Dalgalarrondo et al. 2004). "Downstream," they analyze its effects in vitro and in vivo, thereby helping to develop therapeutic applications.

It is not hard to understand why this division of labor goes together with a numerical imbalance in favor of the chemical, physical and engineering sciences, described in interviews as the "barycenter" of nanomedicine research teams.[23] At a more aggregated level, the same prevalence is found in Web of Science classifications of articles by discipline. The US and France have fairly similar profiles on this point:[24] biochemistry and molecular biology are in no better than fifth place, accounting respectively for 9.6% and 14% of nanomedicine articles, far behind chemistry, materials science, nanoscience and nanotechnology, and physical chemistry. However, it would be excessively functionalist to suppose that nanomedicine research needs directly condition this disciplinary distribution. In the following section I examine the social reasons (competence recognition, task distribution, learning, actor circulation, etc.) for the particularly strong presence of certain specialties.

Interdisciplinarity in the service of disciplinary programs

Interdisciplinary practices are particularly useful in"boundary work"

Nanomedicine research seems particularly useful for the chemical, physical and engineering sciences when it comes to "boundary work" (Gieryn 1983), defined as constructing boundaries between the given approach and alternative ones, boundaries that can then be used to support authority claims and demands for resources.

First, the use of instrumentation and computer simulation in the physical and engineering sciences fuels discourse on the "scientizing" of observation of living things. The first thing to

[23] A field "populated by engineers and physicists," as one biologist I interviewed put it (California, Interview 15, molecular biologist).
[24] See Appendix, Table A1. I selected articles that mention funding by a French or American public agency. This method underestimates publication numbers but targets publications to which French or American authors significantly contributed (as opposed to choosing all articles whose authors indicate an address in France or the US).

be scientized is measurement collection: "biology is [like a] religion if they don't really make real measurements. For example, I was just preparing some lectures. All biology textbooks tell that the lipoproteins of E Coli are located on the peri-plasma surface of the inner membrane. But where is the evidence? We cannot really tell whether this is inside or not. This is imagination, this is religion, this is not science" (California, Interview 16, biophysicist). The complexity of nanotechnology instruments together with the generally ad hoc use of them keep them from being appropriated by biologists and keep biologists dependent on the instrument culture of applied physics (Jouvenet 2007): "From 1990 to 1995, biologists bought techniques and imported them directly. The bionanoscience are a new world where you can take a molecule and manipulate it, etc. Tool development is not part of biologists' culture. And they can't use it like a black box" (France, Interview 15, physicist). Second, data get scientized through computer modeling and simulation, which are very important in nanomedicine when it comes to "making sense of the data" and designing molecules.[25] This is a nanoscience variation on the "dry biology" (informatics) claim to superiority over "wet biology" (lab bench) (Penders, Horstman and Vos 2008), which dates from the beginnings of biomedical informatics during the interwar period (November 2012) and is being exacerbated today with mass biological data processing (Fujimara 2005; Calvert and Fujimura 2011): "We are sort of finishing describing things [so we can] know all of the proteins in the body, the sequence of the DNA. So the next question is, OK, so how does disease work? I believe the answer is to change biology from this descriptive phase to one of quantitation. And that can only work by bringing the principles of physics and chemistry and mathematics and engineering, computational sciences, into biology in a full blown way" (California, Interview 15, molecular biologist). Ironically, nanomedicine researchers associate molecular biology with old-fashioned "naturalists" and collectors—precisely the approach that molecular biology was designed to counter (Strasser 2007). For them, molecular sequences are a contemporary equivalent of life specimen collections (Strasser 2012).[26]

Second, the excellent results obtained in molecule and object design gives credence on some occasions to a discourse on the "rationality" of approaches developed through chemistry, mechanical engineering or materials science, rationality that is then contrasted to the "makeshift" of molecular biology and genetic engineering. This discourse is particularly strong among researchers who link nanomedicine to the synthetic biology program (Calvert 2013): "What sets synthetic biology apart from molecular biology and its closely allied fields of genetic and metabolic engineering is the ambition to formalize the process of designing cellular systems, in the way that traditional engineering disciplines have formalized design and manufacture … To achieve this, synthetic biologists look to move beyond the qualitative and often *ad hoc* engineering pathways that have underlain the slow progress to this point" (Arkin and Fletcher 2006: 114).

Chemical, physical and engineering science researchers are described as those who possess the measurement, simulation, synthesizing and engineering competencies required by

[25] These two functions are crucial in the *Protein folding* project, presented in Box 2.
[26] In the former case, developed in a laboratory rather than kept in a botanical garden or zoological museum.

nanomedicine. They therefore seem particularly capable of meeting the challenges of scientizing and rationalizing biomedical research: “Biology has been populated by people who love description—but we will only move forward if we change that population to add people who love quantification. So, in nanomedicine, engineers, physicists and chemists” (California, Interview 15, molecular biologist). “Coming from physics is a bit easier, because then you can look at five different diseases you don’t know anything about, and look for general principles to create synthetic systems that can mimic biological behavior”(California, Interview 3, chemist). This means that interdisciplinary Masters and PhD programs target non-biologists above all, even when those programs are in life sciences departments: “This Masters program is not only for engineering school students … but also university graduates (biologists, chemists, biochemists, physicists, pharmacists, doctors, etc.) with solid initial training in physics and/or chemistry” (presentation of a French Masters’ program in bioengineering). In response to the view that interdisciplinarity is a radical, urgently needed change, nanomedicine actors (and life sciences engineers generally) express a degree of pessimism about the possibility of integrating the physics or engineering toolbox into biology studies. French and American reports point up the discipline-centered nature of biology training at the pre-doctoral level (National Research Council 2003, 2009; MINEFI 2011) and list impediments to interdisciplinarity. Those impediments are practical (difficulty determining what the biology curriculum should be [Tibell and Rundgren 2010]); epistemological (refusal of some biologists to use mathematical formalism to understand complex biological systems [Guespin-Michel and Ripoll 2000]); and teaching-related (pragmatically adapting curriculum content for students assumed to have no taste for mathematical formalization): “Young people take biology or genetics because they’re less abstract. At one time biologists wanted to reduce the weight of physics in first-year studies in France, also in Denmark and England. Afterwards they realized that [if students] didn’t understand entropy, the second law of thermodynamics in basic physics, they’d be lost” (France, Interview 36, physicist).

The claim in nanomedicine that researchers trained in chemical sciences, physics or engineering sciences have unique competencies also leads departments to give them hiring priority. In France and the US alike, researchers in these fields are in great demand not only with departments in their original disciplines but also in life sciences departments, whereas there is no comparable demand for biologists on the academic job market: “So we have hired faculty in the cell and molecular biology department that will gladly tell you that they have not had a biology class since high school” (California, Interview 25, developmental biologist). “Our bioengineering department would never hire a person with a pure biology degree. We need a technical background, an engineering, math background. We don’t have any faculty from natural science, but in my lab I have graduate students from biology. And their job later might be in biology and not in engineering” (California, Interview 21, bioengineer).

The plasticity or flexibility of the chemical sciences, physics and the engineering sciences and the enlarging of disciplinary boundaries

In importing methods and models from the chemical, physical and engineering sciences, nanomedicine is continuing a long history of conceiving biological objects as inorganic machines (Fujimura 2005). The implication is that living things represent a field for exploration in which cognitive and institutional resources can be used regardless of formal protests against research object impurity: "I attended a meeting called 'Biological Physics: Frontier or Wilderness'. There were several very well-known scientists at that meeting, including a couple of Nobel laureates, and some were arguing that we are making physics 'dirty' by looking at biological systems" (California, Interview 3, chemist). The flexibility of these disciplines considerably facilitates the enlargement of their jurisdiction by means of a "reduction" rhetoric (Abbott 1988) that presents living things as merely one class of objects among others. There are two dimensions to this kind of flexibility. First, none of the disciplines in question focuses exclusively on a specific type of object. Chemistry, described as "a science without a field," has been vulnerable to attempts at annexation throughout its history but is today claiming to be an "architect of matter" (Bensaude-Vincent and Stengers 2001: 330), be it organic, inorganic or hybrid. Materials science is a recent discipline that developed out of the aggregating of several specialties around a concept ("material") defined not in terms of composition but rather properties that make that concept useful (Bensaude-Vincent 2001). Lastly, engineering sciences are concerned with any and all manmade objects (Ramunni 1995), including molecules that perform biological functions. Modeling and reproducing "life's soft machines" (Jones 2004) raises formidable epistemological problems,[27] and scientists from these disciplines working to find solutions to them take their inspiration from either biological or inorganic objects: "So we have always made functionalized nanostructures. Years ago they were for the microelectronics industry, nowadays we make functionalized nanostructures for the biomedical community. The concepts are similar but the applications are different" (California, Interview 7, materials science researcher). "I used really similar concepts when I was working for the food industry to deliver a molecule with precision right next to a seed" (France, Interview 1, pharmaceutical science researcher). Switching from one professional area to a different one like this is generally considered a risky move (Gieryn 1978), but in this case it is understood to enrich the scientist's development. Training or professional experience outside biology is understood to provide researchers with a "grammar" for analyzing living things: "I worked at Bell Laboratories on high speed communication, wireless and optical. I changed my trajectory completely when I started here as an assistant professor. I started working on personalized medicine. People thought I was nuts to do that as an assistant professor, without being tenured, but it turned out okay [laugh]. We started with bioseparation, for example, sorting out bacteria from complex samples, fluids or blood. That involves a lot of engineering, electromagnetics, fluidics, something that I was very familiar with"(California, Interview 24, materials science researcher).[28]

---

[27] The laws of physics are different at the nanometric scale, so it is impossible to transpose engineering principles operating at higher scales to that one.

[28] There is nothing exceptional in this kind of career path, especially in the United States. Five of the scientists I interviewed in California had begun their career in the microelectronics or telecommunications industry and only later started working in biomedical research. The researchers I met with had been trained in chemistry, chemical engineering, materials chemistry, mechanical engineering, electrical engineering, physics, applied physics or biophysics. In California, 10 of the 25

Moreover, these disciplines are directly to be found in "Pasteur's quadrant" (Stokes 1997), wherein basic research is associated with solving material problems (Grossetti 2000). They may therefore be described simultaneously as "fundamental" epistemologically (results are relatively unpredictable and not linked to resolving a specific problem) and "applied" in that they produce knowledge that is useful in object design (Calvert 2006). This dual position dovetails nicely with the instrumental aims of nanomedicine. Cellular and molecular biologists, meanwhile, get relegated to the rank of "invisible technicians" (Shapin 1989; Barley and Bechky 1994): "It's hard to ask large biological questions. A lot of the work centers around what can we do with the nano particles? How do they interact with the cells? It's a lot about toxicology and not so much about biology as a sort of larger question" (California, Interview 25, developmental biologist). "We are often in need of cellular biologists, e.g., for everything related to intracellular traffic… and immunologists. But they don't come into the field very easily, because it's very applied. We outsource, in fact. It's not their research" (France, Interview 13, pharmaceutical science researcher).

Disciplines that manage to extend their territory to encompass life valorize nanomedicine studies in their journals: "With chemistry you easily come out the winner, that's true enough. Having a little bio[logical] data makes it easier to get published, and to get published in a very good chemistry journal (France, Interview 33, chemist). The recognition nanomedicine enjoys is reflected in the number of articles published, the prestige of the journals they are published in and how central those journals are to for discipline. A comparison of chemistry journals and biochemistry and molecular biology journals[29] shows that the former are among the most cited in the field and are published by two major professional associations (the American Chemical Society and the Royal Society of Chemistry). These are either prestigious chemistry journals or nanoscience journals also well known in materials science and physics.[30] Conversely, biochemistry and molecular biology journals do not seem central: their impact factor puts them in the second or third quartile for the field, nor are they published by prestigious biology publishers (e.g., the Nature Publishing Group). These journals clearly function as interfaces between biology, chemistry and materials science, as shown by the fact that one of their publishers is the American Chemical Society and that they are better ranked for the other fields they are identified with (chemistry, polymer sciences, materials science). Biologists, then, valorize their nanomedicine research in the interdisciplinary communities that develop around biomedical technologies or applications, seeing this as at best a change in scientific trajectory, at worst a professional status fall: "A lot of the work has been published in nano-focused journals and novel therapy journals. So they tend to be fairly niche journals. I'm not publishing this work in the journals that I usually publish in, like the developmental biology journals" (California, Interview 25, developmental biologist). "They don't do prestigious biology. And they don't publish in the same journals as biologists who do …

researchers were trained biologists; 6 had also trained in another discipline. In France, 14 in 37 were trained biologists and only one researcher had trained in another discipline as well.

[29] See Appendix, Table A2. I consulted the *Journal Citation Report*, a Web of Science database, to see how these journals were ranked in terms of impact factor, calculated by dividing the number of quotations in the current year by the total number of articles published in the two preceding years.

[30] Journals can be identified with one or several Web of Science subject categories.

embryology or other highly fundamental things" (France, Interview 13, pharmaceutical science researcher). Only biologists who already belong to hybrid communities that include engineering science researchers escape this risk, e.g., bioinformaticians and some cellular biologists working in a type of nanomedicine similar to synthetic biology and publishing articles on the objects they have created.[31]

The chemical, physical and engineering sciences have also been able to broaden their funding base. In some research programs they are explicitly preferred for the generic tools and methods they have to offer: the research teams that we are encouraging to form around this initiative would include a strong engineering component. That is one of the essential features of this, because this is an engineering initiative that starts with a biological base" (Nanomedicine Development Center launch meeting, May 4, 2004). Generally speaking, they benefit from the fact that many grants give priority to technological and therapeutic applications,[32] as reflected in their eligibility and evaluation criteria: "They now have a section called 'innovation' in every NIH grant. From that point of view it has become easier for people coming from outside the traditional biology field to get NIH funding than it was 5 to 10 years ago" (California, Interview 20, bioengineer). Furthermore, the flexibility of these disciplines enables them to apply for a great number of grants, framing their research proposals differently depending on who is funding and proposing a variety of applications for a single concept: "There are things we are doing that, depending who we are trying to raise money from, can be put in a context that is more biomedical or more nanotechnological. We see these more as platform technologies, if you will, that can be used in many different applications, ranging from the biomedical to the biomaterial, to the more diagnostic and analytical side of things" (California, Interview 10, chemical engineer). Biologists, on the other hand, obtain less of the funding earmarked for nanomedicine. Interdisciplinary projects do of course offer opportunities, but biologists do not set nanomedicine research agendas and seldom head publicly funded research programs: "Interdisciplinary projects are often headed by hard rather than soft sciences, so it will be the chemist—associated with the biologist to ensure that the project goes from fundamental science to biological applications" (France, Interview 35, biologist). Funding one's own research program means applying for grants with broader eligibility criteria, for which there is nonetheless heavy competition (ANR "Blanc" grants, NIH R01 grants, European Research Council grants, etc.); disciplinary approaches are more favorably viewed for these grants (Whitley 2010; Stephan 2012): "Except for ANR 'Blanc' grants, we are pretty much forced to collaborate with companies. And the competition for ANR 'Blanc' is getting very, very stiff" (France, Interview 14, biophysicist). "There is not a strong interface between biology and the physical sciences and engineering. Biologists can be very conservative, partly because most of them are funded by the NIH. And they don't want to fund unless you're already halfway towards finishing it" (California, Interview 4, chemist and cellular and molecular biologist).

[31] For example, a *Protein folding* project article on protein assemblies the authors created by drawing on the self-assembling properties of natural proteins published in *Nature Nano*.
[32] For example, ANR grants in specific areas (*P2N*, *Techsanté*, *Nanobio*) and EuronanoMed grants requiring industrial partnerships.

*   *   *

Drawing on the case of nanomedicine, this article analyzes how interdisciplinarity affects disciplinary institutions, thereby at least partially filling a gap in contemporary sociology of science research on interdisciplinary scientific work, which has been focused primarily on the cognitive dimensions of that work. As this article bears on a field in which there are no disciplinarization strategies, it differs from traditional studies on the emergence of scientific disciplines. In the absence of any disciplinary stake in nanomedicine, I have examined the degree to which interdisciplinarity can be a resource for certain "disciplinary programs" (Lenoir 1997), helping the disciplines in question to consolidate and possibly extend their territories. I did not posit interdisciplinarity here to be pure strategy in the service of acquiring power; the point was to investigate how interdisciplinarity modifies scientific community opportunity structures (Dubois 2012).

My empirical study of nanomedicine led me to identify two ways in which interdisciplinarity advances some disciplinary programs. The first concerns interdisciplinary practices. Above and beyond consensus about the scientific value of interdisciplinarity, some types of interdisciplinary work offer means of demarcating given disciplines from alternative approaches (Gieryn 1983). In nanomedicine, measurement and characterization tool complementarity together with method and model importation are particularly effective in activating classic disciplinary contrast representations (quantitative versus qualitative, rationality versus makeshift), with the danger in some cases of producing an overly schematic view. The way some nanomedicine researchers talk about what they suppose to be traditional biology methods does not take into account the plurality of methods and approaches used in the life sciences or the highly fractal nature—both inside and outside the disciplines—of the distinction between "qualitative" and "quantitative" or "soft" and "hard" approaches (Abbott 2006: 43; Dogan and Pahre 1991). Interdisciplinary work gives rise to a rhetoric founded on an old-fashioned view of the sciences as a Comtian "tree of knowledge" in which descriptive and quantitative sciences, general principle sciences and particular ones, are hierarchically ordered (Petit 1994).

The second mode concerns discipline boundary construction and flexibility. Studying what has enabled disciplinary programs to succeed throughout the history of science, Timothy Lenoir notes the importance for researchers of having a theoretical vision broad enough to enable them to do research on a variety of fronts (and therefore to obtain positions in several institutional contexts) (1997: 56). I would point out here that some disciplines develop research programs that help them extend their jurisdiction while minimizing risks for researchers taking up new subjects. For such disciplines, interdisciplinary research offers opportunities of "role-hybridization" (Ben-David and Collins 1966). In nanomedicine, the flexibility of the chemical, physical and engineering sciences (not delimited by a class of objects or phenomena, not defined as conducting either fundamental or applied research) makes it relatively easy for their researchers to gravitate toward new subjects, wherein they assume a position of innovator by importing methods and techniques from their former roles (ibid., p. 459), thereby acquiring strong legitimacy within their disciplinary instruments.

Overall, this study has shown that there is no clear tie between the development of interdisciplinarity and the weakening of disciplinary institutions, and brought to light the ability of some disciplines to move around while maintaining their boundaries. These conclusions corroborate the differentiationist perspective on the sciences (Shinn and Ragouet 2005) and suggest the relevance of analyzing institutional dynamics in science as the combined result of differentiation and unification vectors. Moreover, I would point out that interdisciplinarity impacts on disciplinary territories by way of endogenous and exogenous dynamics, neither of which is stronger than the other. On the one hand, interdisciplinary work and its goals provide disciplines with resources for circumscribing data perimeters and relevant problems and solutions, controlling scientific agenda setting, and securing recognition and rewards. On the other, disciplines continue to be located nearer to or further from institutional and policy agendas that either strengthen or weaken the legitimacy of their research programs and either consolidate or undermine their disciplinary institutions. The chemical, physical and engineering sciences are at the center of the communities of expectation (Van Lente and Rip 1998; Hedgecoe and Martin 2003), hope (Brown 2003) and promise (Borup et al. 2006) that surround nanomedicine; the progressive domination of the instrumental vision among institutional nanotechnology funders works to their advantage. Whereas French and European Union funding was originally used to structure interdisciplinary communities and establish knowledge bases,[33] current programs are working to develop a portfolio of technologies and finalize therapeutic applications:[34] “Over the past years a 'toolbox' has been created that is now available for carrying out further Nanomedicine research and development. Starting from this strong position in research, in the next development phase more emphasis will be needed on translating innovation”,(*ETP Nanomedicine* 2011: 7). Likewise in the United States nanomedicine funding has gradually come to be conditioned on achieving clinical objectives.[35] These disciplines have therefore emerged stronger than before from the shift toward applications in nanotechnology research and innovation policy—even as that shift, perfectly in line with the shift to “mode 2” knowledge production (Gibbons et al. 1994), aims to abolish disciplinary territories altogether: “The first foundational phase (2001–2010), … was focused as anticipated on inter-disciplinary research at the nanoscale. … This phase, dominated by a science-centric ecosystem, might be called ‘Nano1’. The second foundational phase (2011–2020), will be focused on nanoscale science and engineering integration … . This phase is expected to be

[33] In 2004 *Nano2Life*, the first European excellence network in nanobiotechnology, bringing together 23 research institutions and 20 companies, was founded as part of the European Union’s Sixth Framework Programme.

[34] In 2009 the French government launched the national *Nano-Innov* plan aimed at “providing French industry with the means to succeed in the switch to nanotechnology.” It includes a nanomedicine platform at the Saclay Campus and programs chosen to receive funding from France’s “Investments in the future” loan scheme, as well as programs funded by cities like Grenoble and Toulouse. In that same year, EuronanoMed project grants (part of the *ERA-NET*, aimed at developing international, interdisciplinary collaboration) for “reducing the time lag between research findings and clinical or industrial applications for the benefit of patients” were developed in the framework of the EU Seventh Framework Programme.

[35] This holds for NDCs since 2008 (“recently the focus has moved toward application of the basic biological information to specific clinical problems” [Roco, Mirkin and Hersam 2010: 430]) and for studies funded by the National Cancer Institute since 2010.

dominated by an R&D ecosystem driven by socio-economic considerations; it might be called 'Nano2'" (Roco, Mirkin and Hersam 2010: 42).

Séverine LOUVEL

PACTE – Sciences Po Grenoble
1030 avenue centrale
Domaine universitaire
38040 Grenoble Cedex 9
severine.louvel@sciencespo-grenoble.fr

Appendix

Box A1. — ***Method for identifying nanomedicine publications on the Web of Science***

I defined nanomedicine articles as all articles or books dealing with nanotechnology and mentioning one or more biomedical application. In searching the Web of Science I combined two sets of research criteria:

- Grieneisen and Zhang's formula for identifying nanotechnology publications (2011): "nano" in the title, abstracts and keywords; exclusion of publications that clearly have nothing to do with nanotechnology (e.g. *nanoliter*); inclusion of studies with keywords that pertain to nanotechnology (e.g., *quantum dots*, *fullerene, dendrimer*).
- Wagner et al. (2006) criteria for identifying biomedical applications with nanotechnology.

As this last work is somewhat dated, I only used terms indicating general goals and main applications (approximately 75 terms, such as drug delivery, imagery, targeting, regeneration, implant, cancer, HIV, cardiovascular, etc.).

Table A1. — *First five subject categories of articles or books mentioning French or American funding (Web of Science)*

Web of Science Subject category \ Funding Source	France*	United States**
Chemistry multidisciplinary	22	24,2
Materials science multidisciplinary	16,2	21,4
Nanoscience nanotechnology	12,8	18,9
Chemistry physical	14.6	18,2
Biochemistry molecular biology	14	9,6

Note: * 1,400 publications mention ANR, CEA, CNRS or INSERM funding.
** 14,050 publications mention NIH, NSF, Energy Department or Defense Department funding.

Table A2. — ***Analysis of first ten chemistry, biochemistry and molecular biology journals***

chemistry	No. of articles (%)	Impact factor ranking (of 152 journals counted)	Publisher
Langmuir	10	31e	American Chemical Society (ACS)
Journal of the American Chemical Society	6,9	11e	ACS
Journal of Controlled Release	6,7	16e *(10/261 pharmacology and pharmacy)*	Controlled Release Society; Japan Society of Drug Delivery System
Abstracts of Papers of the American Chemical Society	5,4	-	ACS
ACS *Nano*	5,2	9e *(6/135 physical chemistry)* *(9/241 material sciences)* *(5/69 nanoscience and nanotechnology)*	ACS
Journal of Nanoscience and Nanotechnology	5,1	89e *(133/241 material sciences)* *(49/69 nanoscience and nanotechnology)* *(77/128 applied physics)* *(48/68 condensed matters physics)*	American Scientific Publishers
Chemical Communications	4,4	19e	Royal Society of Chemistry (UK)
Nanoscale	3,1	20e *(19/241 material sciences)* *(12/69 nanoscience and nanotechnology)* *(13/128 applied physics)*	Royal Society of Chemistry (UK)
Nano Letters	3,1	8e *(8/241 sciences des matériaux)* *(5/135 physical chemistry)* *(4/69 nanoscience and nanotechnology)* *(5/128 applied physics)* *(6/68 condensed matters physics)*	ACS
Small	3	15e *(14/241 material sciences)* *(11/135 physical chemistry)* *(8/69 nanoscience and nanotechnology)* *(9/128 applied physics)* *(10/68 condensed matters physics)*	Wiley

Biochemistry and molecular biology	No. of articles (en %)	Impact factor ranking (of 290 journals counted)	Publisher
Biomacromolecules	8,7	51e *(8/57 organic chemistry)* *(4/83 polymer science)*	ACS
Journal of Biological Chemistry	5,9	62e	ASBM
Bioconjugate Chemistry	4,6	64e *(13/75 biochemical research methods)* *(27/152 chemistry)* *(9/57 organic chemistry)*	ACS
Biochemistry	4,2	102e	ACS
Macromolecular Bioscience	3	91e *(5/27 material science, biomaterials)* *(9/83 polymer science)*	Wiley

Biochemical and Biophysical Research Communications	2,8	181e *(39/72 biophysics)*	Elsevier
Journal of Molecular Biology	2,7	87e	Elsevier
Analytical Biochemistry	2,4	166e *(32/75 biochemical research methods)* *(26/75 analytical chemistry)*	Elsevier
Bioorganic Medicinal Chemistry	2,4	136e *(20/59 pharmaceutical chemistry)* *(16/57 organic chemistry)*	Pergamon-Elsevier
International Journal of Biological Macromolecules	1,9	163e	Elsevier

Note: For journals listed in several subject categories, impact factors in those categories are indicated in italics.

References

ABBOTT A., 1988, *The System of the Professions. An Essay on the Division of Expert Labor*, Chicago (IL), University of Chicago Press.

ABBOTT A., 2006, "Le chaos des disciplines" dans J. BOUTIER, J.-C. PASSERON, J. REVEL (dir.), *Qu'est-ce qu'une discipline ?* Paris, Éditions de l'EHESS (trad. fr. par M. DROUET de : A. ABBOTT, 2001, "The Chaos of Disciplines", *Chaos of Disciplines,* Chicago[IL] University of Chicago Press, p. 3-33).

AGNEW B., 1998, "NIH Plans Bioengineering Initiative", *Science*, *280*, 5369, p. 1516-1518.

ARKIN A. P., FLECTCHER D. A., 2006, "Fast, Cheap and Somewhat in Control", *Genome Biology*, *7*, 8, p. 114.

BARLEY S. R., BECHKY B. A., 1994, "In the Backrooms of Science: The Work of Technicians in Science Labs", *Work and Occupations*, *21*, 1, p. 85-126.

BARRY A., BORN G., WESZKALNYS G., 2008, "Logics of Interdisciplinarity", *Economy and Society, 37*, 1, p. 20-49.

BEN-DAVID J., COLLINS R., 1966, "Social Factors in the Origins of a New Science: The Case of Psychology", *American Sociological Review*, *31*, 4, p. 451-465.

BENSAUDE-VINCENT B., 2001, "The Construction of a Discipline: Materials Science in the United States", *Historical Studies in the Physical and Biological Sciences*, *31*, 2, p. 223-248.

BENSAUDE-VINCENT B., STENGERS I., 2001, *Histoire de la chimie*, Paris, La Découverte.

BIONEST PARTNERS, 2008, *Étude des applications des nanotechnologies à la médecine*, étude réalisée pour le compte du LEEM.

BLANCKAERT C., 2006, "La discipline en perspective. Le système des sciences à l'heure du spécialisme (XIXe-XXe siècles)" in J. BOUTIER, J.-C. PASSERON, J. REVEL (eds), *Qu'est-ce qu'une discipline ?* Paris, Éditions de l'EHESS, p. 117-148.

BONACCORSI A., 2007, "Explaining Poor Performance of European Science: Institutions versus Policies", *Science and Public Policy, 34*, 5, p. 303-316.

BONACCORSI A., 2010, "New Forms of Complementarity in Science", *Minerva*, *48*, 4, p. 355-387.

BORUP M., BROWN N., KONRAD K., VAN LENTE H., 2006, "The Sociology of Expectations in Science and Technology", *Technology Analysis & Strategic Management*, *18*, 3/4, p. 285-298.

BOURDIEU P., 1984, *Homo Academicus*, Paris, Éditions de Minuit.

BROWN N., 2003, "Hope Against Hype-Accountability in Biopasts, Presents and Futures", *Science & Technology Studies*, *16*, 2, p. 3-21.

BRUNET P., DUBOIS M., 2012, “Cellules souches et technoscience : sociologie de l’émergence et de la régulation d’un domaine de recherche biomédicale en France”, *Revue française de sociologie*, *53*, 3, p. 391-428.

CALVERT J., FUJIMURA J., 2011, “Calculating Life? Duelling Discourses in Interdisciplinary Systems Biology”, *Studies in History and Philosophy of Science part C*: *Studies in History and Philosophy of Biological and Biomedical Sciences*, *42*, 2, p. 155-163.

CALVERT J., 2006, “What’s Special about Basic Research?”, *Science, Technology and Human Values*, *31*, 2, p. 199-220.

CALVERT J., 2013, “Engineering Biology and Society: Reflections on Synthetic Biology”, *Science Technology & Society*, *18*, 3, p. 405-420.

CAMBROSIO A., KEATING P., 1983, “The Disciplinary Stake: The Case of Chronobiology”, *Social studies of Science*, *13*, 3, p. 323-353.

CONESA M., LACOUR P.-Y., ROUSSEAU F., THOMAS J.-F. (eds.), 2013, *Faut-il brûler les humanités et les sciences humaines et sociales ?* Paris, Michel Houdiard éditeur.

CRANE D., 1972, *Invisible Colleges: Diffusion of Knowledge in Scientific Communities*, Chicago (IL), University of Chicago Press.

DE BECHILLON D., 1997, “La notion de transdisciplinarité”, *Revue du Mauss*, 10.

DALGALARRONDO S., GAUDILLIERE J.-P., MOISDON J.-C., PIGNARRE P., PITCHEN P., WERMUTH C. G., CHAUVEAU S., GASTALDI L., 2004, “Problèmes et enjeux contemporains de l’innovation thérapeutique”, *Entreprises et histoire*, *36*, 2, p. 120-149.

DOGAN M., PAHRE R., 1991, *L’innovation dans les sciences sociales : la marginalité créatrice*, Paris, Presses universitaires de France.

DUBOIS M., 2012, *Social Dynamics of Biomedical Research. An Actionist Perspective on the Sociology of science*, Oxford, Bardwell Press.

DUBOIS M., 2014, “*Private Knowledge* et “programme disciplinaire” en sciences sociales : étude de cas à partir de la correspondance de Robert K. Merton”, *L’Année sociologique*, *64*, 1, p. 79-119.

EUROPEAN SCIENCE FOUNDATION, 2004, *Nanomedicine. An ESF–European Medical Research Councils (EMRC) Forward Look Report*, Strasbourg, France ESF.

EUROPEAN TECHNOLOGY PLATFORM (ETP) ON NANOMEDICINE, 2005, *Vision Paper and Basis for a Strategic Research Agenda for NanoMedicine*, Luxembourg, Office for Official Publications of the European Communities.

EUROPEAN TECHNOLOGY PLATFORM (ETP) ON NANOMEDICINE, 2011, *Improving Translation of Public Healthcare Nano-Research in Europe*. White paper.

FABIANI J.-L., 2006, “À quoi sert la notion de discipline ?” in J. BOUTIER, J.-C. PASSERON, J. REVEL (eds.), *Qu’est-ce qu’une discipline ?* Paris, Éditions de l’EHESS.

FUJIMURA J., 2005, “Postgenomic Futures: Translations Across the Machine-Nature Border in Systems Biology”, *New Genetics and Society*, *24*, 2, p. 195-225.

GALISON P., 1997, *Image and Logic: A Material Culture of Microphysics*, Chicago (IL), University of Chicago Press.

GAUDILLIERE J.-P., 2002, *Inventer la biomédecine. La France, l’Amérique et la production des savoirs du vivant (1945-1965)*, Paris, La Découverte.

GIBBONS A., LIMOGES C., NOWOTNY H., SCHWARZMAN S., SCOTT P., TROW M., 1994, *The New Production of Knowledge, The Dynamics of Science and Research in Contemporary Societies*, London, Sage Publications.

GIERYN T. F., 1978, “Problem Retention and Problem Change in Science”, *Sociological Inquiry*, *48*, 3-4, p. 96-115.

GIERYN T. F., 1983, “Boundary-Work and the Demarcation of Science from Non-Science: Strains and Interests in Professional Ideologies of Scientists”, *American Sociological Review*, *48*, 6, p. 781-795.

GODIN B., GINGRAS Y., 2000, “The Place of Universities in the System of Knowledge Production”, *Research Policy*, *29*, 2, p. 273-278.

GRIENEISEN M. L., ZHANG M., 2011, “Nanoscience and Nanotechnology: Evolving Definitions and Growing Footprint on the Scientific Landscape”, *Small*, 7, 20, p. 2836-2839.

GRIENEISEN M. L., 2010, “The Proliferation of Nano Journals”, *Nat Nano*, *5*, 12, p. 825.

GROSSETTI M., 2000, “Introduction : Sciences et “demandes sociales” au tournant du siècle”, *Sciences de la société, Production scientifique et demande sociale*, 49, p. 3-10.

GUESPIN-MICHEL J., RIPOLL C. 2000, “La pluridisciplinarité dans les sciences de la vie : un nouvel obstacle épistémologique, la non-linéarité”, *ASTER, Rencontres entre les disciplines*, 30, p. 87-104.

HACKETT E., CONZ D., PARKER J., BASHFORD J., DELAY S., 2004 “Tokamaks and Turbulence: Research Ensembles, Policy and Technoscientific Work”, *Research Policy, 33*, 5, p. 747-767.

HEDGECOE A., MARTIN P., 2003, “The Drugs Don’t Work: Expectations and the Shaping of Pharmacogenetics”, *Social Studies of Science*, *33*, 3, p. 327-364.

JOERGES B., SHINN T., 2001, *Instrumentation between Science, State and Industry*, Dordrecht, Kluwer Academic Publishers.

JONES R. A. L., 2004, *Soft Machines: Nanotechnology and Life*, Oxford, Oxford University Press.

JONG S., 2008, “Academic Organizations and New Industrial Fields: Berkeley and Stanford after the Rise of Biotechnology”, *Research Policy*, *37*, 8, p. 1267-1282.

JOUVENET M., 2007, “La culture du “bricolage” instrumental et l’organisation du travail scientifique. Enquête dans un centre de recherche en nanosciences”, *Revue d’anthropologie des connaissances*, *1*, 2, p. 189-219.

KNORR-CETINA K. D., 1982, “Scientific Communities or Transepistemic Arenas of Research? A Critic of Quasi Economic Models of Science”, *Social Studies of Science*, *12*, 1, p. 101-130.

LEMAINE G., MACLEOD R., MULKAY M., WEINGART P. (eds.), 1976, *Perspectives on the Emergence of Scientific Disciplines*, La Haye, Mouton & Co.

LENOIR T., 1997, *Instituting Science: The Cultural Production of Scientific Disciplines*, Berkeley (CA), Stanford University Press.

LÖWY I., 1990, “The Strength of Loose Concepts-boundary Concepts, Federative Experimental Strategies and Disciplinary Growth: The Case of Immunology”, *History of Science*, *30*, 90, p. 371-396.

MARCOVICH A., SHINN T., 2011, “Where is Disciplinarity Going? Meeting on the Borderland”, *Social Science Information*, *50*, 3-4, p. 582-606.

MERTON R. K., 1973, *The Sociology of Science. Theoretical and Empirical Investigations*, Chicago (IL), University of Chicago Press.

MINEFI, 2011, *Technologies clés 2015*, Paris, La Documentation française.

MIRKIN C. A., NEL A., THAXTON C. S., 2011, “Applications: Nanobiosystems, Medicine and Health” dans M. C. ROCO, C. A. MIRKIN, M. C. HERSAM (eds.), *Nanotechnology: Research Directions for Societal Needs in 2020. Retrospective and Outlook*, Berlin, Springer, p. 221-281.

MORANGE M., 1994, *Histoire de la biologie moléculaire*, Paris, La Découverte.

MULLINS N., 1972, “Development of a Scientific Specialty. The Phage Group and the Origins of Molecular Biology”, *Minerva*, *10*, 1, p. 51-82.

NATIONAL RESEARCH COUNCIL, 2003, *Bio 2010, Transforming Undergraduate Education for Future Research Biologists*, Washington (DC), National Academic Press.

NATIONAL RESEARCH COUNCIL, 2009, *A New Biology for the 21st Century*, Washington (DC), The National Academies Press.

NOVEMBER J., 2012, *Biomedical Computing: Digitizing Life in the United States*, Baltimore (MD), Johns Hopkins University Press.

OPECST, 2004, *Nanosciences et progrès médical*, Report to the French Senate, 293, rapporteurs : J.-L. Lorrain and D. Raoul, Paris, OPECST.

PENDERS B., HORSTMAN K., VOS R., 2008, "Walking the Line between Lab and Computation: The "Moist" Zone", *BioScience*, *58*, 8, p. 747-755.

PETIT A., 1994, "Genèse de la classification des sciences d'Auguste Comte", *Revue de synthèse*, *115*, 1-2, p. 71-102.

RAFOLS I., MEYER M., 2007, "How Cross-Disciplinary is Bionanotechnology? Explorations in the Specialty of Molecular Motors", *Scientometrics*, *70*, 3, p. 633-650.

RAMUNNI G., 1995, *Les sciences pour l'ingénieur. Histoire du rendez-vous des sciences et de la société*, Paris, Éditions du CNRS.

ROCO M. C., BAINBRIDGE W. C., 2002, "Converging Technologies for Improving Human Performance: Integrating from the Nanoscale", *Journal of Nanoparticle Research*, *4*, 4, p. 281-295.

ROCO M. C., MIRKIN C. A., HERSAM M. C., 2010, *Nanotechnology. Research Directions for Societal Needs in 2020. WTEC Panel Report*, Lancaster (PA), WTEC.

SCHUMMER J., 2004, "Multidisciplinarity, Interdisciplinarity, and Patterns of Research Collaboration in Nanoscience and Nanotechnology", *Scientometrics*, *59*, 3, p. 425-465.

SHAPIN S., 1989, "The Invisible Technician", *American Scientist*, *77*, 6, p. 554-563.

SHINN T., 2000, "Axes thématiques et marchés de diffusion. La science en France, 1975-1999", *Sociologie et sociétés*, *32*, 1, p. 43-69.

SHINN T., RAGOUET P., 2005, *Controverses sur la science : pour une sociologie transversaliste de l'activité scientifique*, Paris, Raisons d'agir.

STAR S. L., GRIESEMER J. R., 1989, "Institutional Ecology, "Translations" and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-1939", *Social Studies of Science*, *19*, 3, p. 387-420.

STEPHAN P. E., 2012, *How Economics Shapes Science*, Cambridge (MA), Harvard University Press.

STICHWEH R., 1994, "La structuration des disciplines dans les universités allemandes du XIX^{e} siècle", *Histoire de l'éducation*, 62, p. 55-73.

STOKES D. E., 1997, *Pasteur's Quadrant: Basic Science and Technological Innovation*, Washington (DC), Brookings Institution Press.

STRASSER B. J., 2007, "Collectionner ou expérimenter ? Les bases de données bio-informatiques dans les sciences du vivant in C. JACOB (eds), *Lieux de savoir*. Tome 1 : *Espaces et communautés*, Paris, Albin Michel, p. 681-703.

STRASSER B. J., 2012, "Data-Driven Sciences: From Wonder Cabinets to Electronic Databases", *Studies in the History and Philosophy of Biological and Biomedical Sciences*, *43*, 1, p. 85-87.

TEISSIER P., 2010, "Solid-State Chemistry in France: Structures and Dynamics of a Scientific Community Since World War II", *Historical Studies in the Natural Sciences*, *40*, 2, p. 225-258.

TIBELL L. A. E., RUNDGREN C.-J., 2010, "Educational Challenges of Molecular Life Science: Characteristics and Implications for Education and Research", *CBE-Life Sciences Education*, *9*, 1, p. 25-33.

TROMPETTE P., VINCK D., 2009, "Retour sur la notion d'objet-frontière", *Revue d'anthropologie des connaissances*, *3*, 1, p. 5-27.

VAN LENTE H., RIP A., 1998, “The Rise of Membrane Technology: From Rhetorics to Social Reality”, *Social Studies of Science*, *28*, 2, p. 221-254.
VINCK D., 1999, “Les objets intermédiaires dans les réseaux de coopération scientifique. Contribution à la prise en compte des objets dans les dynamiques sociales”, *Revue française de sociologie*, *40*, 2, p. 385-414.
VINCK D., 2000, *Pratiques de l’interdisciplinarité : mutations des sciences, de l’industrie et de l’enseignement*, Grenoble, Presses universitaires de Grenoble.
WAGNER V., DULLAART A., BOCK A.-K., ZWECK A., 2006, “The Emerging Nanomedicine Landscape”, *Nature Biotechnology*, *24*, 10, p. 1211-1217.
WEBSTER T. J., 2006, “Nanomedicine: What’s in a Definition?”, *International Journal of Nanomedicine*, *1*, 2, p. 115-116.
WEINGART P., STEHR N. (eds.), 2000, *Practising Interdisciplinarity*, Toronto, University of Toronto Press.
WHITLEY R., 1976, “Umbrella and Polytheistic Scientific Disciplines and their Elites”, *Social Studies of Science*, *6*, 3/4, p. 471-497.
WHITLEY R., 2003, “Competition and Pluralism in the Public Sciences: The Impact of Institutional Frameworks on the Organisation of Academic Science”, *Research Policy*, *32*, 6, p. 1015-1029.
WHITLEY R., 2010, “Reconfiguring the Public Sciences. The Impact of Governance Changes on Authority and Innovation in Public Science Systems” dans R. WHITLEY, J. GLÄSER, L. ENGWALL (eds.), *Reconfiguring Knowledge Production. Changing Authority Relationships in the Sciences and their Consequences for Intellectual Innovation*, Oxford, Oxford University Press, p. 3-47.