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PRINCIPAL INVESTIGATORS AS SCIENTIFIC ENTREPRENEURS[1]

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ABSTRACT

Although Principal Investigators are key actors in scientific fields, there is littlefocus on what they actually do in shaping new scientific directions. This paper studies PIs practices to better understand theirroles.

Our central contribution is to identifythe different ways in which PIs engage themselves in science, in implementing four mainpractices: 'focusing in scientific discipline', 'innovating and problem solving','shaping new paradigms and models'and 'brokering science'. While 'focusing' and 'innovating' remain close to project management, 'shaping' and 'brokering'look more like entrepreneurial activities, shaping new horizons, reshaping boundaries between subfields and among organizations. External orientations to how theyengage in different practices shapes PIs roles to articulate different worlds and to reshape the boundaries of organizations, knowledge and markets.Studying PIs' practices and their

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combinations advances our knowledge about their rolesin managing the interplay between science policies and scientific agendas more effectivelyhighlighting their role as scientific entrepreneurs

Key words: Principal investigator, scientific entrepreneur, practices, engagement, boundary, career path, role, position.

INTRODUCTION

Over recent decades, scientific programming has been split between policy makers - who design priorities through funding programs or agencies - and principal investigators (PIs), who are expected to design and manage research projects to fit with both scientific avenues and national or international priorities simultaneously. In forging research projects, PIscommit resources and energy to buildingresearch avenues, but their role remains ambiguous: are they leaders of projects - or of science itself? PIs are generally the lead applicant in identifying and gaining funding for their projects: the US National Science Foundation sees the PI as *«the individual designated by the grantee, and approved by NSF, who will be responsible for the scientific or technical direction of the project"*[i], underlining their accountability for the execution, managerial and financial responsibilities of projects. But, in contrast, their scientific leadership role remains in shadow.

To better understand PIs' specific roles, we study what they actually do: how they perform their different activities, how they articulate their different role(s) and what practices they engage in the scientific area. Science is changing quickly, andconventional practices are being challenged, so nanotechnologies - commonly viewed as a frontier area of science and as convergent technologies that enhance existing technological competences - represent a suitable empirical setting in which to analyze how PIs' perform science and combine different practices to manage projects, to set up new collaborations and to initiate new scientific trajectories.

We conducted in-depth interviews with sample of principal investigators - men & womenaged between 36 and 59 years, from various institutions and locations, with different backgrounds and levels of experience, holding different positions and - but all involved in leading roles on nano-research programs.

We traced meaning by focusing on PIs' practices, and undertook two related sets of analysis: PIs' activities (what they did) and their motivations (revealed in their career paths, and by their comment on their careers), to identify the dynamics of their actions. Four practices emerged from our analysis: *'focusing'*- deepening understanding within a specific discipline;*'innovating and problem solving'*-developing outcomes and exploiting solutions for existing markets or industries;*'shaping'*- creating new paradigms and models to shapenew trajectories and new markets;and *'brokering'*- animating and influencing their scientific communities. PIs combinedifferent practices to engage in specific roles: thus, when 'focusing' or 'innovating/problem solving' practices dominate, their role is mainly in project management, but 'shaping' and 'brokering' practices enable them to address the challenges of nascent or unexplored fields, building legitimacy and crafting avenues to future researches and new markets.

The first section explores the two dimensions of the paper -practices and PIs' engagement in them -to better understand PIs in action and how they combine their practices in their specific roles. The next section reviews the literature to considerthe specific role(s) of PIs working in areas of breakthrough innovation and radical scientific change, while the third presents our research design for focusing on those practices i.e. discovering how PIs engaged in scientific activities, and what the main motivations behind their practices were, as well as relating the evolution of their involvement in different scientific activities with their careers and career progression. The fourth section outlines the different ways PIsput their specific practices into action, and the final section discusses how they combinedthemto implement different research strategies and to follow their personalvisions of the future of science.

We contribute to the existing understanding of PIs' roles by describing their practices and by reconstructing their roles based on their engagement in combinations of existing practices, which open avenues for them to act as scientific entrepreneurs.

LITERATURE REVIEW

Scientific descriptions of PIs roles of do not necessarily match those that funding agencies expect them to play, so we focus on PIs actual practices to understand how they fulfill their roles, whether as project managers or as scientific entrepreneurs.

PIs as project managers or scientific leaders

Both Shinn and Joerges (Joerges *et al.*, 2000; Shinn, 1988)describe the cognitive division of scientific work by considering the different roles of juniors, seniors,'professors or directors' and 'star scientists' in scientific communities. Juniors pay particular attention to anomalies and to testing existing explanatory models, focusing mostly on one discipline and investigating existing trajectories. Seniors work directly on selecting models and entering data into explanatory models, and must explore different scientific fields to combine them and academic traditions. Professor/directors focus on generalizations, working on fundamental and frequent phenomena, while, finally, star scientists (Nobel prize-winners, professors at prestigious universities) are responsible for designing new knowledge architectures and producing new models from combinations of existing and new knowledge, shaping new paradigms, and brokering scientific activities as scientific entrepreneurs. While junior scientists are usually project managers, star scientists act as scientific entrepreneurs by combining different programs to set up new research streams.

Disciplinary affiliations and career trajectories (their research center affiliations, foreign experience, and the extent of their research collaborations, and scientific and technologic productivity) are key indicators to track the ways in which PIs engage in their scientific careers. All scientists start with intensive involvement in scientific production (deepening existing trajectories), but, as their careers evolve, different individuals take different paths. From this common initial focus, researchers may move to more managerial functions within their organizations; towards acting as scientific managers, serving the community by helping to organize the emergence of new ideas; or moving further on from this focus to an innovating and problem solving orientation, combining different technologies to propose practical solutions to existing - and perhaps envisaged - problems. Siow (Siow, 1998) characterizes the evolution of scientific production as a process of specialization of researchers which follows from the expanding knowledge frontier, and has several noteworthy effects. Hejustifies the tenure system as a necessary 'insurance system' to incentivize risk-averse professors to specialize early in their careers, pointing out that tenured scholars can afford to be less involved in science production and more in organizing it and in innovating in their fields.

If scholars have emphasized relations between careers and the cognitive division of work, funding agencies usually define PIs as project managers. The European Research Council seesa PI as*"an individual that may assemble a team to carry out the project under his/her scientific guidance"*[ii]. As project managers, a PI is the interface between their organization (National labs or Universities) and its funding agencies, managing projects and organizing scientific activities to produce scientific results: as scientific entrepreneurs, they are involved in anticipating the next stages of scientific development and in constructing future trajectories (Frestedt, 2008). They draw on their understanding of academia, governments and industry to broker knowledge, resources and social network contacts, enrolling allies to bridge the needs of their groups, so expanding their role in constructing and executing research agendas into a more strategic and proactive mode, at times creating opportunities where none previously existed.

Thus the image Shinn and Siow hold - of PIs as professors or scientific leaders - does not match the definitions funding agencies have of their activities, which are largely of team and project management functions: we suggest that, to better understand their roles, we need to look more closely at what PIs actually *do*.

Practices: A detour to understand PIs in action

Practices are forms of knowledge qualitatively different from theory and formal knowledge: (Weick, 2003) equates them with doing, concreteness, understanding, know-how - all these in their entirety- while (Wenger, 1998) sees practices as sets of activities crafted in order to get a job done. They involve a significant type of knowledge, which has distinctive characteristics: it cannot be written, taught or explained, but can only be transferred by learning-by-doing, by proximity and imitation, and by trial and error, in situations such as socialization and apprenticeship. Practices refer to sets of competencies that are built in the field, during the process of their implementation: they refer to what is done, not necessarily to what is prescribed - and, we argue, they characterize PIs in action.

Following Latour's (Latour) studies of science in action, we studied PIs' in action. The literature notes four primary characteristics of PIs as leaders: as *scientists* who craft research agendas (Shinn, 1988); as *mediators* who bridge gaps between policy and science; as *project leaders* who manage diverse teams and organizations, steering them via planned milestones to achieve specific goals; and as *architects* and *boundary spanners*conducting activities which resemble those of entrepreneurs in designing the architecture of value creation, delivery, and capture mechanisms(Bozeman *et al.*, 2004; Carlile, 2004; Mangematin *et al.*, 2012; Scarbrough *et al.*, 2004). PIs form hypotheses about the evolution and future organization of science, and assemble skills and resources, funding and equipment, and support from past contacts and heterogeneous allies to set up platforms, initiatives and projects which can capture these emerging trajectories and so participate in creating future scientific arenas. PIs may be involved simultaneously in most of the different practices identified in the literature - but the degree and balance of thatinvolvement is key to understanding what PIs do, beyond just supportingthe different actions and the involvement of their organizations. (Jian *et al.*, 2009) have defined PIs roles as the combination of practices in which scientistsare involved - and noted that these are likely to change in line with their career paths and their seniority, and also to according the organizations and scientific communities with which they are affiliated.

The fundamental changes that have taken place in public sector research in recent decades have seen scientific research increasingly organized around different models of *academic entrepreneurship*(Jian *et al.*, 2009; Lam, 2010; Shane, 2004) - usually defined as practical and direct contributions made by university research to society - which have seen university scientists increasingly engaged in commercial activities and the growth of university-industry relationships and technology transfers. Scientific entrepreneurs differ from academic entrepreneurs - while the former are involved in commercialization of science, bridging academia and markets by creating start-ups based on academic results (Franklin *et al.*, 2001; Shane, 2004; Shibayama, 2010; Wright *et al.*, 2004; Catherine *et al.*, 2004), *scientific entrepreneurs* remain within academe, where they shape new research avenues and new scientific trajectories, proposing new ways for science to interact with industry and more broadly with society (Callon *et al.*, 2001).

Engagement in practices shapes PIs role

The degree of PIs' engagement in different practices contributes to the emergence of their roles. The notion of engagement has a relatively short history, but it is a unique and important motivational concept, which we define as the intentional performance of actions so as to be thoroughly involved in a focal pursuit, task or initiative.In this context, the notion encompasses PI's job involvement (in tasks and activities), the satisfaction and pleasure they gain from their work and theirintrinsic motivation to perform the work and adhere to its value system (Crawford *et al.*, 2010). But - we argue - even this is not sufficient: even if it is impacted by a certain value congruence, the essence of an individual's engagement relies on their personal vision of the world and the potential, personal contribution they can make to its progress(Ashforth *et al.*, 2008), and how this is then articulated within organizational settings. This fuller definition thus includes the choices scientists make to engage with different communities or organizations - universities or institutions, wider academic communities or in creating relationships with the wider economic world (Knorr-Cetina, 1982).

Practices are the lower unit of analysis of what PIs do: their roles can be defined as the combination of practices they employ. The ways scientists engage in combining (or not) diverse practices, in overcoming organizational constraints to engage themselves simultaneously in several communities to implement their particular vision of what is to be done, provides a clearer picture of their research strategies and their contributions to science.

DATA AND METHOD

Research design

The field of Nanotechnology is growing rapidly, so it provides a good opportunity to analyze an emerging field where trajectories remain open and Principle Investigators have to make strategic choices according to their scientific vision or career ambitions. As a multi-purpose technology, nanotechnology creates much uncertainty - but also many opportunities - for both stakeholders and scholars. To study their practices, we need fine descriptions of their actions; but to limit organizational heterogeneity, we have focused on four main organizations - one national lab and 3 university centers. To gain key information about the trajectories of their scientific careers, we collected data - both through interviews with PIs, and from their publications - about the history of projects in which they had participated.

Data and Methodology

We interviewed 20 PIs (for between 90 and 140 minutes) using semi directed questions. We focused first on their career trajectories – their initial training, promotions and overall career achievements - and on their socializing habits and, from that general discussion, gained an understanding of their personal goals in performing science and how they made sense of their professional activities. Our second level of analysis focused on their professional practice, as the only tangible way of observing their actions within and among organizations, looking particularly at what changed rather than what was stable i.e. on the evolution of their practices and activities, and on aiming to make sense of those evolutions. The interview guide was structured along four key patterns of scientists' actions(Latour, 1991; Latour *et al.*, 1979):

- *Producing science*: PIs 'produce' science, technologies and innovations, and the outputs of their activity are measurable (numbers and quality of articles, of patents and innovations, and of the turnover they generate). While 'doing science', PIs are involved in dialogue with the academic scientific community (by writing scholarly articles, participating to or organizing workshops and conferences, supervising PhDs, etc.), while in filing patents and innovations, they interact with firms and other players in the wider economic environment..
- *Building legitimacy:* This dimension concerns how researchers and PIs *"gain legitimacy for what they do"* (Suchman, 1995). Scientific legitimacy can come from PIs' positions in their scientific fields; hierarchical legitimacy from their organizational positions, from which they launch programs or involve researchers; and outside legitimacy fromtheir relationships with industry or with policy makers.
- *Interacting with actors and communities:* This dimension (closely related to the previous two)includes those with whom the PI interacts: are they mainly peers from

the scientific community, or firms and the economic community – or are their interactions more highly diversified?

- *Envisioning*: This dimension represents PIs' medium and long term scientific visions and perspectives, and includes how they frametheir overall scientific ambition as series of projects which match the requirements of public authorities, and how the growing use of projects as coordinating mechanisms leadsthem to develop specific sets of abilities.

We asked the PIsto describe their practices within each ofthese patterns, to weight their comparative involvement in each pattern at different stages of their careers and to relate themto other changes (in organizations, scientific evolutions, etc.).

Data Collection

Data were collected in two stages - first, the choice of the study sample, and second, the collection of archival data and interviews with the selected PIs, all of whom are involved in nano research programs at a limited number of institutions and locations (the research centers of National lab and of universities in Paris, Toulouse and Grenoble). Aiming to map the diversity of their situations, we selectedPIs with different backgrounds (engineers, doctors from various disciplines, chemistry, physics, biology, etc). Becoming a Principal Investigator represents a significant achievement in a scientific career, so all were in the senior stages of their careers, but they still represented a heterogeneous sample, as they held different positions in public research institutions, and haddifferent levels of experience (mostly senior scientific researcher, scientific director, head of research group, academic executives). Exploratory work includedtesting our interview guide and desk research about each interviewee to gather detail for our criteria measures. All interviews were prepared from data available on the Web and ISI-WoS, and were semi-directed and structured around open questions on subjects' careers, their nano-technological orientations, their positions in their discipline, and their history of project management, activities and principal responsibilities. The second data collection phase consisted of transcribing and analyzing the interviews (average 11,336 words), using an inductive and deductive approach which relied mainly on Nvivo qualitative analysis software. We focused first on our observations, searching for similarities and differences to describe PIs' careers and practices, identifying and linking the constants and the repeated themes that were meaningful to the nature of their engagements. We then extracted elements describing their practices (and the drivers of those practices)to produce a comprehensive synthesis of variables of PIs' engagements and related research strategies to identify their roles comprehensively.

Data analysis

We used NVivo9© to maintain a database and manage our data analysis in a systematic and consistent manner. The software enabledus to code the data (interviews) and to manage the emerging codes, and generated findings iteratively (the biogs were coded manually).Our analysis followed a three-stage process ensures we understood PIs' roles more completely.

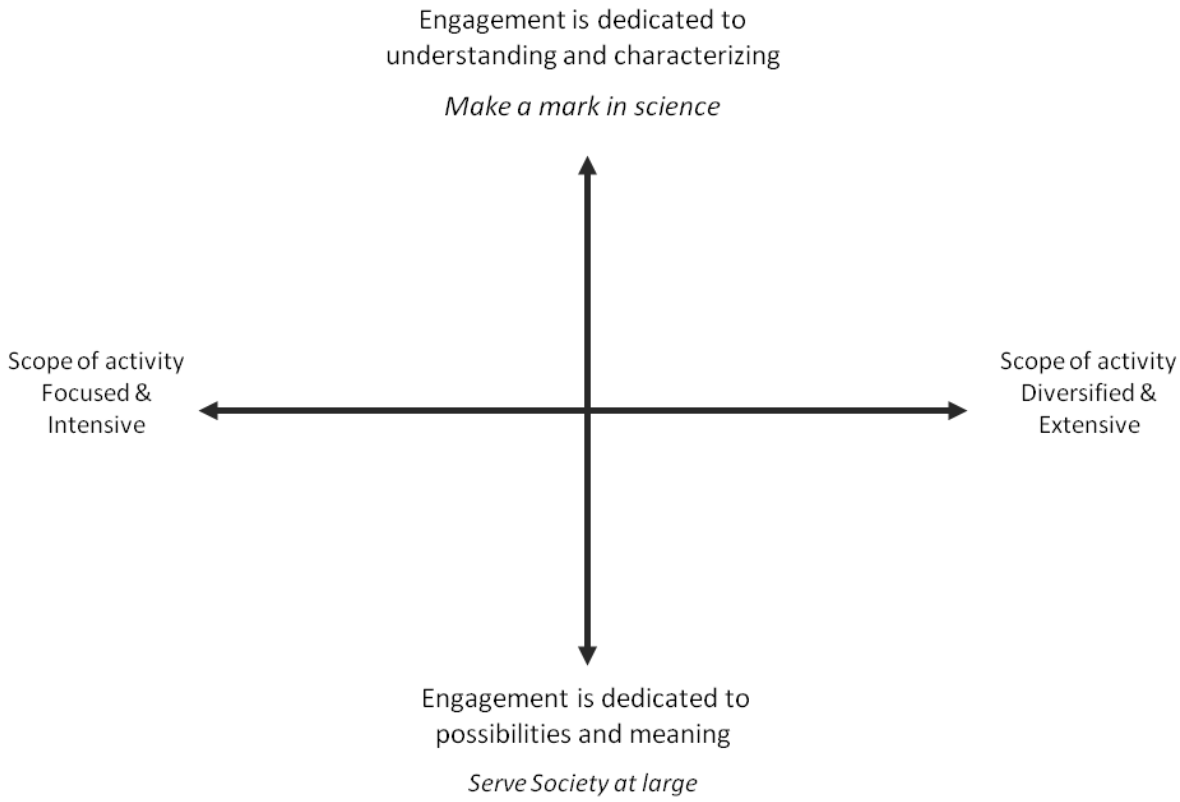
Stage 1: Segmentation of PIs' activities

We coded PIs' activities, the choices that differentiated their practices and their career paths (i.e., how they engaged in those practices). Each career item was labeled and categorized according to its associated practices, in line with our interview guideline segmentation: *production* encompassed numbers and quality of articles, grants, patents,andinnovations; *position*, including all activities designed to build legitimacy, (within or beyond the scientific community) - conferences, referees, publishing strategy (medium, articles, books, etc..); *interactions*within the scientific or non-academic communities; *anticipation* including planning and time management, whether PIs invested in several projects at once or not, and how they deploy themselves overdifferent time horizons .

Stage 2: Positioning of practices on two dimensions

As Fig. 1 illustrates, two dimensions structured PIs' practices: the scope of their activity and the locus of their engagement. Their 'scope of activity' (on the horizontal axis) indicates the extent to which scientists concentratetheir activity, from an intense focus on scientific production, to being more broadly active in a range of different domains, i.e. management of scientific institutions, interactions with actors outside academia (e.g., firms) or the scientific community at large. The second dimension describes the nature of PIs' 'engagement with science' (on the vertical axis) - whether they are keen to 'make their mark' within science, by increasing scientific knowledge, giving their name to particular scientific laws or running the Nobel Prizes competition or by developing the wider meaning of science, and the possibilities if offers society at large. The vertical axis of Fig 1 represents PIs' degree of openness to non-academic dimensions, while the horizontal axis maps out the degree of their focus on science performance (experimentation, computing results, writing articles, etc.).

Fig 1 Mapping practices



Stage 3: Practicesor set of homogenous practices

The last stage is to analyze how scientists engage in the different practices and combine them along their careers. We group practices which are similar to emphasize four different*sets of practices*: ourResults are summed up in the various tables presented in the following paragraphs.

RESULTS

The identification of four different sets of practices

Our analysis of the PIs' interviews and profiles allow us to map out research strategies in terms of their socialization processes, research topics and fields, how they produce science and perform research, and how they interact with various communities (Fig. 1).Fig.2 locates the *sets of practices*(which are detailed in the following paragraphs) along the two dimensions of focus and scope.

- *'focusing'*- deepening knowledge within a discipline,
- *"innovating and problem solving"* - exploiting outcomes and solutions for existing markets or industries,
- *'shaping'*- creating new paradigms and models to shape new trajectories and new markets,
- *'Brokering'*- animating and influencing the scientific community.

Fig 2: Four sets of practices

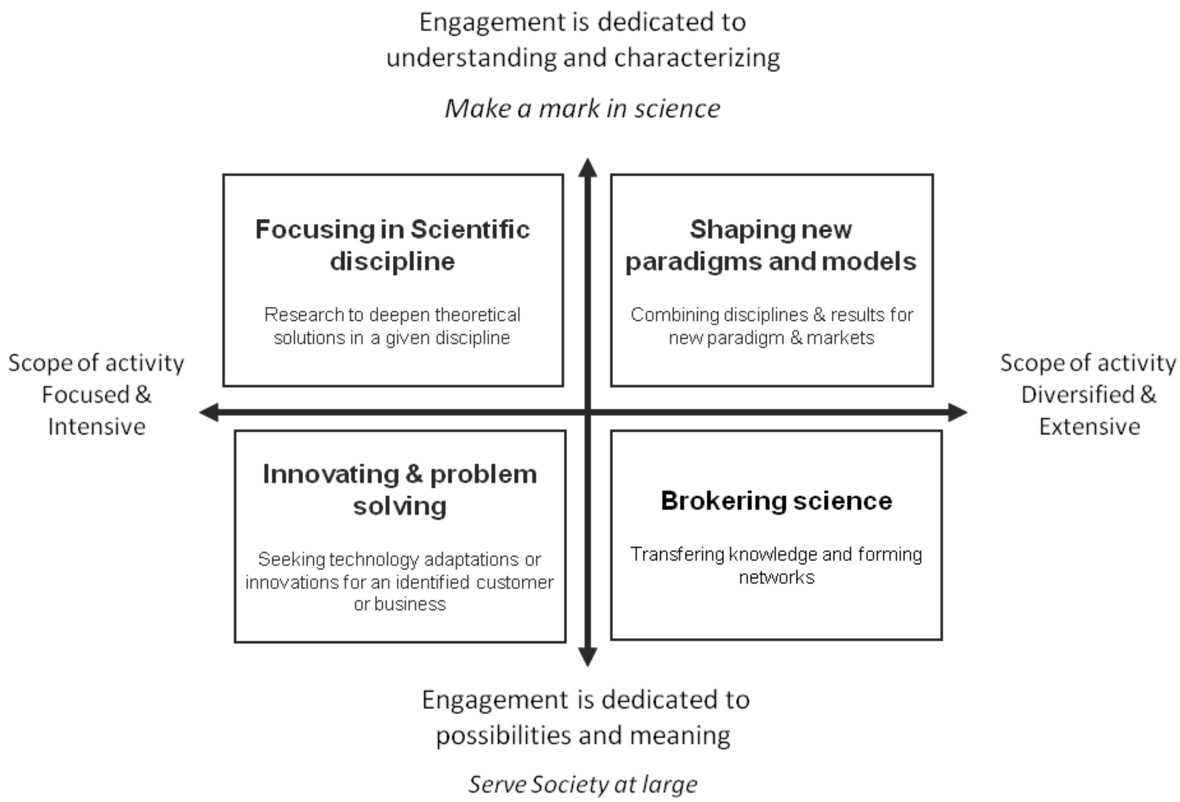


Table 1 gives the characteristics of the practices (following the categories of the interview guide) which are detailed in the following paragraphs."

Table 1: Practice characteristics

	Focusing in Scientific discipline	Innovating & problem solving	Shaping new paradigms and models	Brokering Science
Production	Scientific production within the discipline	Production bridging scientific disciplines and industry	Mostly designing projects and involving scholars to manage them and perform science. Theoretical production	Accompany the emergence of new paradigm by forming new networks, bridging heteronomous actors and forming new organizations
Position	Legitimacy from publication and peer recognition	Legitimacy comes from problem solving and satisfaction of the networks (amount of money)	Legitimacy comes from the ability to organize projects to shape new trajectories and to make them accepted in the scientific field	Legitimacy comes from the ability to bridge heterogeneous actors to anticipate and engage innew trajectories
Interaction	Within the scientific community of their discipline	At the nexus of different networks. Translation mechanisms from industry concerns to scientific questions	Interactions with industry, and with different scientific communities	Interaction with heterogeneous actors, shapingnetworks, alliances
Envisioning	Anticipation of the scientific	Anticipation of ways to solve problems for actors	Organize project to implement their own vision of the evolution	Prospective view and strategic anticipation of emerging networks.

	results of the project		of science	Enabling role

Focusing on a scientific discipline: deepening knowledge

Practices in this set focus on scientific production in a specific disciplinary field- Table 1A presents their main characteristics and some relevant quotations from interviewees. Researchers formulate their research questions to answer knowledge gaps within their discipline and contribute to existing theories by producing articles or patents, but their aim is not to shape new scientific trajectories: as Popper argues, they are engaged in exploring anomalies. Such practices do not promote radical novelty - rather they aim to deepen knowledge within an already given trajectory. As nanotechnologies are still an emerging field, scientists generally interact within their original disciplines, with few contacts with other communities,or different disciplines or laboratories: *"I am a physicist, my formal training is in quantitative physics and I stay within this subject. I must preserve my knowledge and expertise".* But as the field evolves (changing themes, laboratories, etc.), scientific researchers feel uneasy: *"I have to make a big leap to change subject – that's difficult for me*". PIs' legitimacy comes from their ability to publish articles in their communities' journals, and mostly takes the form of peer recognition of their research ability. Their anticipation capabilities remain low - the question "*where do you see yourself in ten years"* generates fuzzy answers: *"It's a good question....I don't currently think ten years' ahead."*Activities are mostly confined to their academic fields, where they focus on developing and implementing their vision of the future of the discipline.

Innovating and problem solving:exploiting outcomes for existing markets

The engine that drives thesepractices comes from unsolved problems,generally more technological than scientific, and usually raised by industry:Table 2A presents their main characteristics. Research activities are usually developed within structured organizations, which are involved in technology transfer and technological development with industry, producing intermediary results to be used by firms in their innovation process and patents that can be licensed. *"The way we work... we've got the program managers, who we talk to... then there's the departments and a proper hierarchy"* Fields of work are already known, where much work has been done over time, often under different labels, with little novelty and few potential new opportunities. Practices are not designed to produce scientific results per se, but rather to exploit existing knowledge to produce solutions, and so are structured by the problem solving approach, which aims to combine different bodies of knowledge to respond to the needs of identified clients.*"Yes, in literature, we could predict…But here it happens naturally, we have the material, we have the potential application, and we just have to put it together..."* Practices thus resemblethose of engineering science, using theories to deliver practical results, to bring solutions to the technological requirements of industrial clients. The innovating and problem solving orientation of such research efforts are chiefly about identifying the most effective technologies in specific markets and ensuring they are incorporated effectively, although that may require developing those technologies furtheror converting them to fit new contexts. In summary, practices are about combining technological artifacts, having in mind the actual (or potential) customer. Connections with industrial partners are strong, as are collaborations with equipment manufacturers: the aims are to solve problems or adapt industrial devices. Such research efforts typically produce a bricolage of practices with short and medium term horizons.

Scientists conform to organizational goals, while scientific directions are set by the environment, and interact mostly within their organizations and with their clients.Researchers serve their organizations, and express themselves through impersonal statements. *"I've spent my career in my organization – I'm an organization clone…"* There is little reflection on experience or on the actual field of nanotechnologies – rather, energy is directed towards the collective service of the institution, with scientists aligned to their policies or hierarchies: *"There's the boss and everyone else steps into line".*Researchers gain legitimacy from their ability to solve clients' or partners' problems, and their vision remains limited, as projects are set by project managers and scientific options are designed by scientific advisors. Anticipating the scientific futureis seen as the realm of the institution, which determines the research choices and overall directions - PIs anticipation capabilities are mainly directed towards finding ways to match clients' and partners' expectations.

Brokering science: Transferring knowledge and forming networks

In this set of practices, (outlined in Table 3A) nanotechnologies are perceived as offering opportunities to develop radical, breakthrough innovations, and particularly to promote new business models which can challenge dominant industry logics (Sabatier *et al.*, 2012). *"For me, nanotechnology is the means that I exploit to do things…I need to do things which should be useful for someone…"* Brokering sciencepractices describes situations where PIs create collaborative networks which combine different bodies of knowledge to develop artifacts or new technologies, exploiting existing stocks of knowledge and experience developed through interactions and connections: *"… it develops through direct interactions, conferences, seminars…or I work through my colleagues who have their own networks and who can propose interesting ideas…"*Practices are not only embedded in existing networks, but also shape collaborations for the future *"What I am looking for is a global perspective and an exploratory approach."*, and researchersplay active roles in understanding and detecting what is emerging. The production of multidisciplinary knowledge is not the aim - rather the focus is on creating modular platforms within which different elements can be integrated (Baldwin *et al.*, 1997; Joly *et al.*, 1996; Langlois, 2000; Richard *et al.*, 2005). Collaborative practices are anticipated and built up, so scholars must make strategic decisions about with whom they should ally: *"There are similar ideas which are complementary and which should be brought together, otherwise we will have projects within projects…"* Networks are at the heart of such collaborations, informing both the interactions involved in the projects in hand, and extending beyond them. PIs guide such communities of knowledge via a double approach, combining immersion and overview, which enables them to stay at the center of the field, perfectly interfacing with events, whatever their nature. *"I need to keep a strong image but to be able to enlarge the field without losing competences…"* Legitimacy comes from PIs' ability to anticipate the evolution of science, to coordinate these evolutions and to broker its fields, scholars with partners beyond academia i.e. to anticipate scientific development and so provide their co-workers with vision and a sense of the future.

Shaping new paradigms and models: determining new trajectories and new markets

As noted in table 4A, this practice involves the fuller expression of PIs' scientific ambitions, combining extant and forecasted projects to serve their intrinsic goals. PIs following this practice have their own visions of where science should develop and they combine resources to try to make them happen. They are strongly involved in the management of knowledge, and in defining or modifying knowledge models to build scientific trajectories: *"AFM is a laborious, complex experiment requiring theoretical explanations for my results… You have to find models, which is complicated, and that's perfect for me."* Nanotechnologies are perceived as opportunities to set up new trajectories, to escape from conformism and institutional pressures: *"At the moment there's an overlap between the scales: because there are the two routes, up and down, and that has generated an exchange between fields"*. This practice aims at going beyond the limits of traditional disciplines: PIs' scientific curiosity and confidence in their abilities to think 'outside the box' are important drivers: *"How does that* *work, what are the mechanics, what energy does it need? We know how to do it with a laser, a magnetic field, pressure..." "My initial training is robust enough to enable me to .....I'm curious; I need to understand, to know that it's possible".* Researchers immerse themselves in interactions with the scientific, social and economic worlds, revealingmarked capacities for anticipation and the sense of connection to the future. Theyoften have a relatively limited emotional distance from their subjects, expressing themselves in the first person, and are passionate, expressing pleasure and emotions. *"A desire to make a mark, which the world will remember... I don't want to be remembered for the Big Bang, but for a discovery which could have an impact on the socio economic world."*

Their desire to be in the midst of science is their most significant driver, and their intuition and the outcomes of repeated transactions shape their practices, which are rooted in an elevated level of transverse knowledge of science. Their legitimacy comes from their ability to organize projects to nurture and implement their anticipations. Such scientists consider their contribution as a mission, as a way to change the world.They not only work on the foundations of new trajectories, but also to make sense of what happens, of the evolution of the science. They develop simultaneously - both scientific capabilities to produce challenging scientific results which set up new trajectories, as well as political experience in building new networks and gaining influential positions within them.

Scientists are more or less involved in each set of practices. At the start of their careers, the emphasis is on scientific production, but their trajectories become more diversified after gaining tenure or professorships. Some PIs play roles which are more involved in the scientific community at large - managing academic associations or being editor of journals - others are more dedicated to university or research organizations management, and others are more concerned withtransferring knowledge, and influencing the interactions between science and society at large. It is thus important to map out how they combine theirpractices and to characterize their main trajectories.

From practices to roles

The engagement of PIs in different practices, and the progressive development of those practices (and those engagements)can be seen as continua of activities, which are enriched as their seniority progresses.The initial stage is always a 'digging'phase, when scientists focus on results in their field, and have to demonstrate their ability to produce original results, to socialize within the scientific community and to publish in good journals. Some scholars remain highly focused on such scientific production, gaining ever-greater expertise in limited arenas:as PIs, they play 'experts' roles, as central references in specific knowledge niches, methodologies or instruments. (SeeTable 1B).

Being involved in their scientific community, they can invest more in community interactions, which corresponds to them moving on towards internal managerial functions, whether in their own organizations or in the scientific community at large.In addition to science production, scientists can deploy their practices both within the scientific community but also in interaction with policy makers, firms or the society at large. PIs develop capabilities to interact with more heterogeneous networks, and act along existing trajectories, within extant communities or organizations. These are 'given' and so usually stable: uncertainty remains low, and PIs can quickly learn whichfacts are relevant and which questions must be asked and answered. The skills they implement resemble those of project management: their role is to represent their organization and to design efficient management mechanisms to perform research, which will include developing skills in collaborating with existing teams or scholars, project planning, accurate estimating and cost control, project control and execution, effective problem management, and building and growing a high-performance team. PIs evolution is based on deepening those capabilities they originally developed to ‘dig into’ established scientific trajectories,as Table 2B illustrates.

In interacting with non-academic actors - such as policy makers, socio-economic actors or industry - PIs movebeyond their scientific trajectories. The second possible evolution of theircareers is to develop their practices outside the academic arena, to address insteadquestions from policy makers or firms with scientific gaps and research questions. They develop practices such as innovating and problem solving as they become more connected with industry, and move towards more unstable environments, where scholars combine heterogeneous fields to produce novel and emerging knowledge. In such contexts, where research agendas are defined by industries(or by individual firms), the heterogeneity of partners and networks increase uncertainty, as does the need to bridge different disciplines to solve problems and to innovate. PIs engaged in these paths usually spend part of their careers as industrial researchers, and are likely to move to and fro between academia and industry.

Finally, some PIs combine all these different practices simultaneously, and develop the capabilities to shape new paradigms. Shaping scientific field demands that they experiment, interact with a wide range of different partners(firms, policy makers and the society), and participate in the construction of meaning and theory. Such PIs must simultaneously performing scientific research, and at the same time make sense out of their actionsso they can speak about them to the field (by publishing, responding to ongoing debates, attending conferences to present results and new theories to peers*, seeTable 2B*). Likewise, they will discern developments in Intellectual Property issues, and identify possible new trajectories. Such ‘PI-entrepreneurs’ generally have their own scientific objectives, and will be working towards - or will have reached - positions from which they can mobilize projects to nurture their scientific ambitions. In combining different practices, they are characterized by their mobility and openness to all practices, and the inherent high levels of uncertainty involved provide them with more freedom to combine resources, reshape boundaries within and between fields, and to label investigation territories in ways that will appeal to funders and other players. They will be able to bridgeinstitutional and organizational boundaries to combine or discriminate technologies and markets, transcending their pure scientific role toshape and form new expectations in wider communities. Some act as Knowledge Brokers and implement very distinctive skills: they know how to operate partnerships with both institutions and individuals, they can define and modify knowledge models and adapt devices, and they know how to promote innovation by building blueprints and managing knowledge communities, designing knowledge architectures and making tacit knowledge explicit, etc..

PIs as scientificshapers: scientificentrepreneurs.

Academia has focused on *academic entrepreneurship* as a way of commercializing science by the creation of science-based start-ups (Jian *et al.*, 2009; Lam, 2010; Shane, 2004):*entrepreneurial science*(Etzkowitz, 2003) is usually seen as referring to university-industry linkages, and specific programs have been designed to train scientists to create start-ups to promote such commercialization. Academic institutions need PIs with entrepreneurial capabilities to develop their activities within academia, to shape scientific avenues, to engage stakeholders and make sense to them. S*cientific entrepreneurship*, as a way of shaping new trajectories or new paradigms, requires the capabilities to perform and to make sense of science – both to address specific problems and to give sense to ongoing-strands of work.We define *scientific entrepreneurs* as scientists with entrepreneurial capabilities,but who work within academia who not only perform research, but are also involved in acquiring resources from different sources (funding agencies, firms, professional associations, etc.), in combining internal and external resources to shape scientific avenues, and in gaining legitimacy for these new avenues by organizing workshops, conferences, special issues or setting up new journals, building on their scientific reputation to transfer it to other networks (economic, business, policy makers). In these ways, they shapeand 'enact' their environments by changing the boundaries of organizations and setting up new ones.

Are scientific entrepreneurs born – or made? Scientists are mostly trainedon how to perform science, to explore within given trajectories, aiming to become expert in specific disciplines. The cognitive value of science exists in theories, precision, details, measurements, experimentations and technologies, but the academic segmentation between fields and sub-fields reinforces the barriers between them and leads to the 'siloeing' of scientific knowledge(Tippmann *et al.*, 2012). Scientists learning processes are mostly 'on the job training', which fits well with the basic expectations for project and program management, but other skills and profiles are required to address challenges in nascent or unexplored fields, and to deal with uncertainty. Although some scholars have become scientific entrepreneurs with no specific training, such preparation may be necessary to enlarge their number and improve their success rates – such training may be inspired by business techniques for spotting high-flyers (identification of high potential and talents, coaching and mentoring to guide middle managers toward top management), to support career pathways more precisely, and to detect qualities in candidates that might fit them to make the transition from project management to the orchestration of scientific research programs.

Are scientists born to be PIs – or can the skills be learnt? Such questions raise the problems of career management and knowledge transfer. In controlling researchers' activity, attention is sometimes paid to management indicators that differ from economic valuations of research. By characterizing the relevant practices and identifying the different nature of individuals' engagements with science, we have drawn attention to the enrichment of PIs' practices and to their deploymentin different worlds as way of changing their roles in academia from producer to scientific entrepreneurs. The nature of research has changed dramatically in the modern era: science is now being 'made' across cultural, occupational and geographic boundaries, and this global shift has increased stakeholders' and scientists' interdependence, as their roles are increasingly embedded in ever-broader social systems (Weick, 1979). Scholars repeatedly note that the consequent increased uncertainty and unpredictability can rarely be controlled through systems – in fact, it is individuals who are at the forefront of shaping new research avenues.

Learning and gaining familiarity with other ways of doing things can be structured around the sharing of practices to help cope with change, but such sharing demands a new mindset and a new perspective on scientific production. Sharply defined, the answer to the training needs noted above would be neither an extra training program on project management, nor a tactical kit to allow candidates answer calls for tender more successfully. We would argue rather for sessions where PIs can share best practices, reflect on their own strategies, discover other ways of doing things, and enhance their interactions with PIs from other backgrounds. Participants would then be able to gain a deeper understanding of the stakes and challenges involved in taking on the dual role of working both as a researcher and as the actor who shapes research agendas and programs. The purpose would be to reveal wider sets of practices (following research work on PIs in the field), to identify key points and to develop adapted strategies (involving resources, team management, interaction and networking) to meet complexity and challenges.

CONCLUSION AND FURTHER DEVELOPMENT

Our central research question concerned how Principal Investigators managed to organize and coordinate research, how they handled different modes of collaboration and faced today's growing complexity, paradigm shifts (such as upheavals in funding systems) and the expanding universe of knowledge. Our argument was based on the idea that there are different ways for PIs to engage in Science, one being rather more tightly focused, the other relating to interactions in wider scientific diversity and to ‘making sense’ of science. PIs’ roles may differ significantly according to the nature of their engagement - from that of project manager to that of scientific entrepreneur, linking different worlds and different activities to cross the borders of knowledge.

By describing and analyzing PIs core practices and roles, we highlight how they determine the essential meaning behind their research projects and programs. Their involvement in scientific production – in terms of articles, patents, etc - and in the interface between (perhaps fluctuating and dissociated) socio-economic communities can enable them to take on focal Roles as knowledge brokers, act as pathfinders to overcome differences in those communities’ interests, ambitions and directions, making sense of complex knowledge and surfing shifting territories to cross establishedknowledge boundaries.

Analyzing PIs’ current positions and roles allows us to improve our understanding of the relationship between engagement and performance, and to make sense of innovation management in relation to organization and HR management: managing both individuals’ progress and flexibility and collective performance based on team complementarities. Further research could focus usefully on increasing mobility and absorption capabilities, which supposes using dedicating resources to manage career stages and to foster interdisciplinary collaboration. The specific skills appropriate to different styles of engagement (as we have defined it) include mobility and swiftness, a taste for encountering the outside world and a talent for promoting partnerships. The nature of PIs’ engagement can be seen as that of an evolutionary researcher, one ready to meet the current challenges of science in action.As scientific entrepreneurs, they are shaping their environment, according to their vision.

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APPENDICES

Table 1A: FOCUSING IN SCIENTIFIC DISCIPLINE

Practices Types:	Data exemplars for First Results
Practices focused on scientific production in a particular field	*"I'm a physicist. I graduated in quantum physics and that's where I've stayed…", "You have to preserve your expertise…"* DP1EN; *"The lab hired me to work on carbon nanotubes…"* MP3FP; *"My field is sugar chemistry… I have the culture of sugar chemistry and assembly in aqueous solution."* AG1CV
Little contact with other communities	*"I haven't found a way of changing field…"* DP1EN; *"this patent could have interesting medical applications, but that's not a priority in my work"* AG1CV; *"Yes, I already knew the team I did my post-doc with, and in fact I'm still working with them today… yes, I've been in the same team all along"* MP3FP
Some difficulties with change	*"I had to make a big leap to a different subject… I find it hard…"* DP1EN; *"They come to me to solve problems that need my skills… but don't necessarily involve the same subjects and I find that quite hard…"* AG1CV
Individual projection into the future is uneasy, practice is not reflexive	*"That's a good question… I don't really imagine myself in ten years' time at the moment"* DP1EN; *"It's not something I think about"; "I'm very happy in my job, so I don't think about the future all that much… I think that I'll think about it more if there are changes in research…"* MP3FP
Changes in the organization of the research can raise questions about practices	*"I'm fed up with the hypocrisy. I spend a ridiculous amount of time managing projects. I don't work in admin. I spend time looking for contacts… If we want people to study hard sciences, we might have to look again at working conditions…"* DP1EN; *"I'm learning to position my work internationally… to get my articles in high-profile journals…"* AG1CV; *"So I thought that was a good way to get a PhD student… it's interesting, but it also disperses…"* GT3CE

Table 2A: INNOVATING AND PROBLEM SOLVING

Practices Types	**Data exemplars for First Results**
Identifying with a community (initial social group or the community of the research institution)	*"I thought, well I could do an ENS"* DP1EN; *"I've always worked at CEA, never worked anywhere else…"* BP1LE; *"I'm in materials… my academic network is a constant in my life… I use it an awful lot."* MG3LE
Nanotechnology: more a new label than a new field	*"They talked about condensed matter…"* MG1IN; *"We are more and more confident in micro technology so naturally we are moving into nanotechnology…"* CG2LE; *"During my doctorate, I was already working on nanomaterials based on silicium."* MP3FP
Little thought given to experience or field of nanotechnology	*"Then I started a PhD, but France Telecom was privatized… and I'd done my military service at the CEA"* CG2LE; *"history just led us into nanotechnology…"; "It just happened like that; I didn't wake up one day and decide to do nanotechnology…"* GT3CE
Energy directed towards the collective or institution	*"I'm from a public sector background, so I imagined that I would work in the public sector too…"* DP1EN; *"At the CEA, they sell man-years"* MG3LE
Forward planning delegated to the institution, which makes decisions and defines strategy	*"There's the Group leader and everybody else at the same level"* GT3CE; *"The way we work… we've got the program managers, who we talk to… then there's the departments and a proper hierarchy The science can wait."* MG3LE
The relationship with fundamental science takes the form of a search for consistency with established theories	*"Yes, you can say that this was predicted in the publications… Then it all happened naturally: people said here's the material, here's the potential application, let's make it work…"* RP1LI

Table 3A: BROKERING SCIENCE AS SCIENTIFIC ENTREPRENEURS

Practices Types:	**Data exemplars for First Results**
Practices focused on problem-solving, across different subjects.	*"I'm a chemist who landed up in physics"* MT2CE*;* *"I've always wanted to be able to indulge both my love for quantum mechanics and fundamental science with the ability to make devices"* CP1LM*;* *"How does it work, what is the mechanics, what energy does it need? And we can do it with a laser, a magnetic field, with pressure…."* BT1LC
Moving on from their original field is driven by PI's confidence in their abilities and by curiosity	*"My initial studies were broad enough for me to leave the field… I'm very curious; I really need to understand stuff, to know what is possible…"* MT2CE*;* *"I did engineering, but I wanted a bit of latitude in some areas…"* BT1LA*;* *"I wanted to change. I want to move on; I don't want to stay in the same place…"* SP1LM
Nanotechnology provides an opportunity to take part in the social process (need to be useful)	*"For me, nanotechnology is a means of doing stuff… I need to do things that are going to be useful to someone…"* SP1LM*;* *"It's good to fund projects, but what is the position of this science in society?"* BT1LC
Researchers set targets in the scientific, economic and social worlds	*"You always want to come up with something that people remember. I don't want my name to be associated with the Big bang, but with a discovery that could affect the socio-economic world…"* SP1LM*;* *"What I want to do is come up with a new solution… Quite simply, I want to change the world…"* BP1LE
Ability to plan ahead is expressed and there is a marked relationship with the future	*"I was preparing my future… I've got to look 15 years ahead…"* SP1LM*;* *"So in twenty years it'll be a motor, in ten years it'll be the memory, because there's still integration work to be done, in three to four years it's the photonics…"* BT1LC*;* *"It's in the posters, I look at the new projects, and you see things take shape"* MT2CE
Low emotional distance from the subject (tone is passionate; pleasure and emotion are palpable)	*"So we went and bugged these molecules to get them to do stuff for us. Why? Because we can..."* BT1LC*;* *"Yes, the unexpected result was the switch, and it was huge!" "I found hard disk technology incredible exciting, like fine metalwork…"* RP1IE*;* *"I really liked the people here, because they are so dynamic…"* SP1LM

Table 4A: SHAPING NEW PARADIGMS AND MODELS

Practices	Data exemplars for First Results
Search for meaning, turning tacit knowledge into explicit knowledge and defining or altering knowledge models	*"AFM is a laborious, complex experiment requiring theoretical explanations for my results… You have to find models, which is complicated, and that's perfect for me...”*MT2CE*;* *"At the moment there's an overlap between the scales: because there are the two routes, up and down, and that has generated an exchange between fields…”* BT1LA
Nanotechnology: an opportunity to learn, and to break down barriers between subjects	*"I want to learn, and that's also what attracts me to new projects"* CP1ES*;* *"I have a transversal tendency; I want to link different subjects… that's how you get new ideas, by using analogies in different subjects."* BP1LE
Strong links to the future, active analysis to understand and detect emerging trends	*"I sit on national and European committees, so I see what people are doing, the good trends, the good ideas…"* BT1LA*;* *"I'm looking for a global view and a prospective approach."* BP1LE*;* *"I spend my time reading… keeping up with science and technology…"* RP1IE
Network lies at the heart of interaction (a supportive stock of experience in various arenas for interaction and connections).	*"It happens in direct contact, conferences, seminars… or I go through my colleagues who have their own networks and can make useful suggestions…"* SP1LM*;* *"bibliographical tools tell you for the next five years who has quoted your paper, who is using it, and if you don't know them, you click on their name and see their bibliography…"* BT1LA
Collaboration practices are prepared and planned	*"Your group needs to be efficient enough to bring an idea to fruition. You have to be able to admit to now knowing how to do something. You have to be brave enough to give the idea to someone else who can help you develop it."* BT1LA*;* *"When you're working on a project, everybody has to make their contribution, but there remains the difficult task of coordinating and harmonizing… You have to show that people are working together and not just next to each other…"* SP1LM
Steering knowledge communities maintains a central position in the field	*"There are some things that are complementary and similar; there has to be at least a bit of a gap, or you end up doing projects within projects…"* GT1CE*;* *"…you need to keep a fairly high profile, but widen your field without losing your expertise. I follow about forty journals all the time and I look at every abstract…”* BT1LA

Table 1B: FOCUSED ENGAGEMENT

Trajectory:	**Citations about scientific evolution**
Initial education tends to be fundamental	*"My thesis was basically about lasers rather than quantum optics, and I became interested in making micrometric lasers with a very low threshold, using doped materials and rare earth elements"* TP2EN
Community firmly rooted in a particular field	*"My focal point is the AFM microscope; everything else is secondary to me…"* GT3CE
Career fairly closed to contact outside the community	*"It's not that I don't want to… but it's a massive job, running a European project is huge, and I don't think I've got the time for it…"* MP3FP; *"you have to get a company interested in the projects, well no not right now, …I don't see who, so tough, I'll do a generic project (ANR Blanc)…"* DP1EN; *"Well, let's say that I didn't fight to get to be a coordinator…"* TP2EN
Change directed by the environment (in response to the environmental constraints)	*"So then I looked for somewhere to go… and then I got a chance to join a new lab…"* TP2EN *"It was closer to home, so I took the plunge… I thought I was away quite a lot when I was doing crystals with molecules…"* DP1EN; *"At some point, you've got to establish skills that make sense, that hang together…when people tell us to look at a particular subject, we just follow the herd."* MG3LE
Alignment with the institution, (impersonal expression)	"We file more patents than we publish articles…" MG3LE; "If you want to be top dog in LEDs you've got to file patents" CG2LE; "In those products we're world leaders…"; "Our goal in our department…, they trained us...they told us…" RP1LI
Creating the requisite conditions for greater stability as response to uncertainty (career geared towards transmission and teaching, more local involvement…)	*"I like my role of academic supervisor, where I can no longer… but in the end I don't really miss it…"* DP1EN; *"It's easier to work locally…"* MG3LE

Table 2B: DEPLOYED ENGAGEMENT

Trajectory	Citations about scientific evolution
Careers are structured by personal challenges	*"I've got a very personal vision of where I want to go… I don't want to do the same thing as everybody else, otherwise…"* CP1ES
Education is often unusual, at the interface between different academic or scientific fields	*"When I finished my doctorate, the CNRS and the University of Tokyo had just signed a partnership deal…"* BT1LA; *"So in 2005, I went to Silicon Valley for two years in industrial research"* RP1IE
Engagement skills are inextricably linked to where PIs work, to their positions	*"Then you've got to find your niche, because the way I see it there's the vision of the politician, and then there's the vision of the researcher, and the researcher can have an overview of an interesting field, but then they still need a vision of what they can contribute… Is that useful? Is that doable? You have to find a trade-off between the appeal of the subject and the competitive advantage…"* CP1ES
Involvement is often international	*"Fundamental research is global"* CP1ES
Subjects question learning in order to break down the boundaries of knowledge	*"If you asked me to do something grown-up, like be an engineer for example—without being pejorative—working with really established stuff, I wouldn't like that… which is surprising because I studied engineering"* BT1LA
Subjects field often encompasses the entire chain from pure to applied	*"The team itself can cover the entire chain, from the material, which is macroscopic, and can then be nanostructured, to study its properties… and then we can measure it, i.e. link it to the outside world, characterize it… then say how we can integrate it into actual technology. After that we go to the manufacturers, who can build a prototype, so we really cover the whole chain… "* RP1IE *"Our job is to take scientific risks to move science forward…, even in the long term, so not everybody can do it, but I have that characteristic…"; "Selling things that have already been made is not research…"*CP1ES *"I'm going to sit on everything I did before and look at things differently"* GT1CE

[i] http://www.sfi.ie/funding/grant-policies/sfi-investigator-titles/
[ii] Provided by EUROPE DIRECT Contact Centre/ Research Enquiry Service