Software's 'Functional Coding' and personnel mobility in technology transfer: linkage fields between industry and publicly funded research

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Abstract: This paper shows how publicly funded basic research programs develop complex 'linkage fields' over time. The dynamics of these linkage fields generate multiple possibilities of technology transfer that depend on their specific characteristics. On the basis of one of the 30 case studies done in the context of our DOE study, the 'Synthesis and Optimization of Chemical Processes' housed at a US university and funded by BES, this paper shows how the development of a linkage field leads to a specific form of technology transfer via personnel mobility. The production of software creates a special form of 'functional coding' that facilitates the recontextualization of personnel from publicly funded research to industry and vice versa. This case suggests the 'linkage field' as a unit of analysis in the assessment of the impact of publicly funded research.

Keywords: Technology transfer; tacit knowledge; codified knowledge; impact of research.

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1 Introduction

For many years it was simply assumed that publicly funded R&D (PFRD) would have beneficial economic impacts while it served various missions set by government policy. More recently, this assumption has been challenged and there is a demand for evidence that such benefits accrue. In order to increase the economic impact of publicly funded research activities, there is a need for greater understanding of the mechanisms by which the knowledge they create benefits the for-profit sector. Policy makers and scholars have focused on the linkages between industry and PFRD as the primary channels for such economic benefits to materialize. The nature of these linkages has been investigated in considerable detail producing a large body of literature on the facilitating factors and obstacles to the process of technology transfer and innovation leading to new marketable products.

Most of the work on such linkages takes the point of view of the firm that uses knowledge to develop innovative technologies and products. This is a rather narrow focus because many of the legitimate outcomes and impacts of PFRD are not perceived directly from the standpoint of the improvement of businesses' bottom line. At the same time, the strategic behaviours observed are those of people in business who decide how to pursue collaborations or establish linkages in order to take advantage of PFRD for their innovation objectives. Of course, this narrower focus does legitimately undermine the sweeping claim that public funding of basic research leads inexorably to greater economic benefits via innovation. When the industry lens is used to sift through PFRD activities much of what occurs there is irrelevant and most of what is used in industrial innovation does not originate in PFRD [1,2]. In response, numerous models of innovation have been developed to replace earlier simplistic assumptions. They attempt to show how knowledge flows from various sources and in various vehicles resulting in new commercial technologies [3,4].

The prevalence of this point of view, however, does tend to solidify a stereotypical view of PFRD as having a culture and incentives that constitute obstacles that must be overcome for a successful transfer of knowledge to the for-profit realm [2, pp.20–22]. As a matter of fact, basic research activities are enormously variegated and defy those neat categorizations. Very few PFRD activities today, which the practitioners identify as basic research, have a single focus or goal [5]. So, as Pavitt has maintained, an important step that needs to be taken in order to understand the economic usefulness of basic research is to move away from viewing science merely as an information creating activity [6, p.118]. Even when the focus on linkages between industry and PFRD is pursued from the perspective of the individual innovating firm, it need not always be the case that the preponderance of basic research in PFRD is of limited utility for commercializable inventions in the relatively near term. Our research has also shown that, with proper division of technical roles during cooperation, significant commercial impacts can be obtained from partnerships in which a public sector research team performs basic research [7]. Studies of laboratories in the public sector by Laredo and colleagues [8], Crow and Bozeman [9] and Joly and Mangematin [10] show the variety of strategies and goals they pursue as well as the various types of interaction with industry they may have.

This paper attempts to show how publicly funded basic research programs develop complex 'linkage fields' over time. The dynamics of these linkage fields generate multiple possibilities of technology transfer that depend on their specific characteristics. On the basis of one of the 30 case studies done in the context of our DOE (Department of Energy) study, the 'Synthesis and Optimization of Chemical Processes' housed at a US university and funded by BES (Office of Basic Energy Science), this paper shows how the development of a linkage field leads to a specific form of technology transfer via personnel mobility. The case study was developed through multiple in-depth interviews with principal investigators and other participants in the research efforts plus a detailed analysis of project documentation covering the life of the stream of research, such as proposals, publications, résumés, and activity reports.

The linkage field in this case is closely tied to the technical focus of the research and its characteristics determine the broader impact of the program. The main products of the research are algorithms and software packages to simulate and control large-scale chemical processes. One of the characteristics of the linkage field is that the software allows for two-way mobility of people between research and industry. This suggests a peculiar type of codification in software, 'functional coding', that has some characteristics of codified scientific knowledge and some of tacit or embodied technological knowledge. The case study is presented in the next section and further analysis of its implications for the connection between types of knowledge and technology transfer via personnel mobility follows.

2 The case of the synthesis and optimization of chemical processes: software's 'Functional Coding' in technology transfer

The 'Synthesis and Optimization of Chemical Processes' is a research program conducted at MIT under the direction of Larry Evans, from around 1976 to 1991, and of Paul Barton, from 1992 to the present. The main concerns of this research are the flows of energy in industrial chemical plants. It seeks to develop systematic methods to synthesize industrial chemical processes and provide optimal solutions for the required overall energy flows. The visible products of this research are specifications and software packages that implement the methods and algorithms to reach optimal solutions.

2.1 Software-mediated interdisciplinarity

The name given to this field of work by the practitioners is 'computer-aided chemical engineering'. It involves the use of powerful software tools for the development, design, operation and control of chemically-based manufacturing processes. Even though the substantive applications of this work fall inside the field of chemical engineering, the research activities related to this case are truly interdisciplinary. The main contributions are not in the chemical processes themselves. The research topics involve mathematical modelling techniques and specifications for chemical processes most of which are of interest to industry. Chemical engineering provides the background know-how about the chemical processes, including physical properties, thermodynamics, and the chemistry and physics of the processes. Numerical mathematics provides the algorithms for solving the equations and other mathematical problems that result from the implementation of the processes at an industrial scale. Computer software engineering enables the implementation of computer software that is robust, reliable, and effective.

The development of techniques for computer-aided chemical engineering fall into three areas: simulation, optimization, and synthesis. The goal of simulation is to predict the performance of a proposed or existing plant using mathematical models to carry out the heat and material balances. Steady-state simulation and plant-wide dynamic simulation were developed during the early stages of the program and software packages used in industry are commercially available. The simulation of batch and semi-continuous processes is still in its research stages. Optimization is at a higher level than simulation. In any proposed flow-sheet there are many degrees of freedom in the selection of design and operation parameters and many tradeoffs in the proper choice of values for these parameters. Optimization seeks to balance these competing forces to maximize an objective function such as profit. Before optimization can be performed, it is necessary to know the structure of the flow-sheet. The conception of the structure of the manufacturing process is a task in process synthesis, which is at the highest level.

A consequence of the nature of this work is that it results in generic or 'infrastructural' technologies that can be applied in other fields completely unrelated to the one that guides or motivates the original research. The sets of equations that model a chemical process may be found, with some variations, in other systems and the mathematical techniques and optimizing algorithms to solve them are portable. Similarly, computer software implementation requires solutions that are not inherently dependent on the particular chemical problem it is originally designed for and can also be transferred to other situations. The research program studied in this case has only partially exploited this, but the awareness of this possibility suggests that many links will probably develop in the near future. According to the researchers, communication across disciplinary lines still has its difficulties and exchanges could be much more fluid than they now are. Problems in the design of VLSI integrated circuits, for instance, are very similar to the ones encountered in designing large chemical process plants. However, most innovations in modelling and simulation in this area have originated in chemical engineering rather than electrical engineering.

The production of algorithms and software gives the field distinct characteristics that both connect and separate it from the engineering and pure science fields it combines. The research qualifies as basic or fundamental according to conventional definitions because the researchers maintain that they do not work to solve problems posed by industry. It is intellectual interests informed by a complex environment that guide problem selection and research priorities. However, the production of algorithms and their software implementation have features of both codified knowledge, as they must be specified and written in a programming language, and of technological artefacts, that require tacit knowledge to operate correctly. They have both abstract, universal features and concrete, localized features that are essential. The knowledge produced in this research program is hybrid both in nature and form having significant features of both basic and applied, and codified and tacit knowledge.

At the same time, the production of algorithms for systems such as simulators and optimization packages, provides a vehicle for the convergence of disciplines with very distinct emphases when taken separately. In this case, fundamental chemistry provides the set of mass and energy equations for the system. Chemical engineering provides the practical knowledge for adjusting and optimizing flows in the particular combination of heat exchangers, reactors, pipelines, boilers and other devices of a chemical plant. Numerical mathematics addresses the techniques for solving the sets of equations that result when the particulars of the chemical systems and the physical plant are factored into their formulation. Software engineering provides design techniques appropriate for implementing large-scale software systems such as the ones that are required for these sorts of problems. In other words, the production of algorithms and software mediates a particular form of interdisciplinarity, which this case exemplifies.

2.2 *Linkage field of the research program*

The origins of this stream of research can be traced back to the second half of the decade of the 1970s when the US DOE sponsored a significant amount of work in alternative fuels in response to the energy crisis. Private firms in the chemical industry sector participated in the funding for this research program from the beginning. The goal of the initial project was to develop software for synthetic fuels processes and optimization of energy flows in chemical plants. Both subjects were directly related to priorities set by the energy crisis. The work resulted in the development of a simulator for large scale, steady state, commodity plants. The program would calculate the solution to the energy balance equations for the entire flow sheet of a plant.

By the end of the first five year period, the emphasis on energy crisis priorities began to wane and DOE discontinued support for this line of work. Evans and his team had developed the simulator and wanted to continue developing their ideas and programs, including their relationship with the industries interested in the results of their work. The path toward the commercialization of the simulator was clearly in view at this point but could not be housed entirely within the institutional framework of MIT. Evans, then, decided to start a business to pursue the commercialization of the simulator and its future versions. As a result, Aspen Technologies Inc. was founded in 1981 while Evans was still a professor at MIT. The company developed the simulator for commercialization and also developed plant control versions of the software that could not only simulate the energy balance conditions but also introduce integrated control loops to control the plant once it was implemented.

The fundamentals of the Aspen technology were used by other commercial enterprises that were founded to provide competing products. Therefore, the impact of the original research into energy balance sheet simulation was not simply a single spin-off company to commercialize the product but an entire industry segment that provided a family of products, which varied in sophistication, price completeness, and other features. Aspen Technologies was challenged by the competition to conduct its own R&D to improve its product line as well as learn from the basic research which continued at MIT. The link between PFRD and industry that was established was not a one-to-one relationship across a well defined interface between a private firm and a publicly funded research team. Rather, a multidimensional and multifaceted set of links between PFRD and industry emerged with the creation of a new intermediate industry sector that owed its existence, at least in part, to the nature of software.

The commercial impact of this PFRD can not be subsumed under the creation of a spin-off company either. The spin-off company and its competitors that constituted the new intermediate industry sector not only served the larger chemical industry sector by providing software products and services. They also brought to the attention of the research team at MIT new cases and problems that could be related to their research interests. As a result, the research program also grew and it generated collaborations in basic research with teams housed elsewhere.

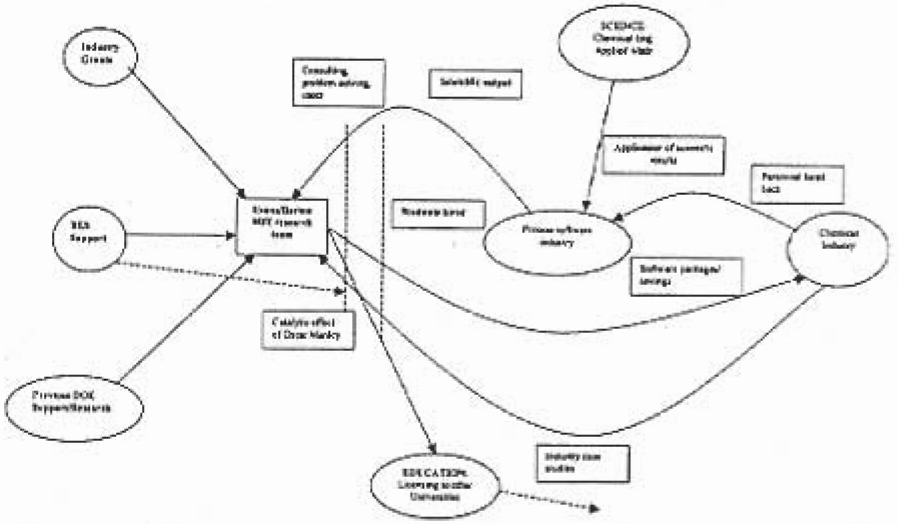
After the start up period of the enterprise, Oscar Manley, the program manager for the division of Engineering at the BES, suggested that Evans develop a partnership effort with the Idaho National Engineering Laboratories. BES would fund it to continue the research component of plant energy integration and batch process modelling and optimization. This collaboration began in 1985 and continued for about ten years.

During the period beginning in 1985, the oversight role of Manley was very important because he managed a coordinated program at the engineering division of BES. The projects he supported were not simply selected among a population of unsolicited proposals based on their individual merit. Manley took a proactive role in encouraging submissions that were complementary and contributed to overall goals in energy-related engineering research. He was very supportive of research that ultimately was used in some way by industry and gave Evans and his team great flexibility in licensing results of BES supported research for commercial ventures. It must be kept in mind that, during the entire period of BES support for the basic research in expert systems and process modelling conducted by Evans, he was also the president of Aspen Technologies. This commercial involvement proved to be instrumental in the high industry impact of this research. However, Evans maintained that it was an intellectual agenda rather than commercial or industrial priorities which determined the direction of research under BES grants. Therefore, the position of Evans and his team created feedback channels from the chemical industry sector both to the spin-off company, as a part of the supplier-client relationship, and also to the research program at the university where they could draw on a rich collection of experiences for selecting research problems. Similarly, the competition in the intermediate industry sector, in which the spin-off company belonged, also provided knowledge and information both for their product development and the university research team.

The problems they addressed in the first period of BES funding were general interest expert systems problems that had no direct applications to industry issues of interest to Aspen Technologies. They were in the area of energy integration in order to balance the uses of energy in a chemical process. The main uses of energy in these cases are heating and/or cooling material to the temperatures required for each stage of the process. Later, the emphasis shifted to modelling batch processes and the overall design problem of plants to implement the batch processes. The feasibility of the latter result was clear when the use of their models in a plant simulator achieved results very similar to those used in plants that had been subjected to very long processes of optimization. A design package based on these methods promised to achieve in a single iteration what took years of field adjustments in the plant. The savings in production costs for the chemical plants by using these software packages is in the hundreds of millions of dollars a year. This indicates that software simulation codifies the tacit knowledge used in previous optimization processes.

In sum, this case is certainly an example of linkage between industry and PFRD with high economic impact due to the implementation of process innovations that profoundly changed the way chemical plants work allowing them to achieve much higher energy efficiency. The linkage, however, cannot be characterized with a simple industry/PFRD collaboration. Rather, we are in the presence of a 'linkage field' with multiple organizations and multiple loops of knowledge and technology transfer. The dual role of the academic-entrepreneur that created the first company while continuing with the research certainly led to the creation of externalities via the spin-off of research and the self-reinforcing mechanisms sustained through his dual role. However, the emergence of an intermediate industry sector, with multiple competing companies that performed their own R&D and implemented research results in software packages is a key feature of a complex pattern that transcends the role of this individual (see Figure 1 for a representation of the linkage field).

Figure 1 Linkage field of the research program



2.3 'Functional Coding' and the flow of people

The great economic impact of this research is not only due to the innovative algorithms and software packages that it produced. The career paths of students that participated in this research were highly significant. They were an integral part of the transfer process because they accompanied the development, implementation, and installation of software. They were hired by Aspen Technologies and its competitors in the intermediate industry sector that developed commercial software with the skills acquired doing research as members of Evans' team. Graduates in this field are still in great demand both for the companies that develop commercial software based on the results of basic research and in the chemical industry at large in order to apply the software intelligently to the particular cases of a plant or a firm.

As we already mentioned, Evans has a very large consulting portfolio as well and is able to bring particular case studies or new problems from industry for students to work on in their theses. The feedback from industry available through Evans' connections would be interesting enough. However, in a striking pattern of personnel exchange, still another much more substantial feedback channel exists. Over the years, students who did graduate work with the research team have been hired by competitors of Aspen Technology in the same industry segment or by firms in the chemical segment and later hired back either by Aspen Technologies and even returned to research work. The communication network of graduates plus the actual career path returning to the MIT-Aspen centre has maintained this stream of research in very close connection with the relevant industrial sectors magnifying its impact potential enormously.

The fact that people are accompanying the products in the entire development, implementation and application path indicates that there is a significant tacit knowledge component. The software companies are able to retain the knowledge embedded in the packages they deliver to the chemical industries and these do not attempt to develop these software packages in house. This indicates that the knowledge embedded in these software systems is highly appropriable. Even when the packages are sold to the chemical industries and applied by them, they are not only unable to reproduce that knowledge to derive future versions themselves but also need people familiar with their development to make the application successful in their context.

The technology transfer problem is often construed as overcoming the obstacles that knowledge produced by PFRD encounters for it to become relevant and useful in industry. In this case, the relevance and utility of the PFRD is not as problematic. The people and products from the research environment can readily come in and make a difference in the industrial setting without actually giving away the knowledge. So, together with the highly tacit characteristic that requires the flow of people with the software, there is another feature that seems to facilitate the mobility from the research context to the application context that is generally associated with codification. The process of optimization that was done over a long period of time involving the experience (tacit knowledge) of plant managers could now be completed and outperformed with a single iteration of the simulator. At the same time, it is not obvious that researchers who know how to develop algorithms and their software implementations for complex systems of equations could easily find their way around a chemical plant with boilers, pipes, valves, and large volume of chemicals. This is allowed by the 'functional coding' of software that operates as a counterpart to the tacit dimension and facilitates the flow of people and knowledge. The 'recontextualization' is mediated by the simulator that incorporates and codifies the tacit knowledge of experienced plant managers.

In sum, the research activities in this case have some important features that distinguish it from typical notions of either basic or applied research and either codified or tacit knowledge. The career paths of graduate students and postdoctoral researchers who participated in the research follow rather unusual patterns facilitated by the 'functional coding' of the software that results from the research. This characteristic points to one of the often overlooked ways in which PFRD creates value: the creation of scientific and technical human capital [11]. The research program described here shows that new career patterns are generated by the research activities that involve complex relations between the public and the private sector.

3 Technology transfer and the diversity of knowledge and linkages

3.1 Software simulation and the nature of scientific knowledge

The use of super-computers in scientific research has led to the creation of a new type of activity that has not only practical but also epistemological consequences. Super-computers allow scientists to develop simulations of natural processes and the operation of technological systems at such a level of detail that have become very realistic. These simulations enable the manipulation of systems that cannot be confined within the boundaries of a laboratory. This is the case, for example, with the explosion of nuclear devices or the dynamics of atmospheric phenomena. These simulations have acquired an epistemological status in science that differs from both experimentation and theory

building, though it contains elements of both. Many scientists have called this the 'third way' of science, with experiments and theory being the first and second ways [12]. The legitimacy of simulation for the production of certified scientific knowledge was not achieved overnight. It was the result of a fairly long process of more than a decade in which scientists educated under an aesthetic of science that valued closed analytic solutions had to give way to a younger generation that learned to value the visualization of numerical solutions. This process had consequences, not only for the day to day practice of research in certain fields of science, but also for the policies concerning the building of infrastructures for scientific research [13,14]. In this paper, the importance of the 'third way' of science provided by simulation lies in how it affects the discussion about the nature and transfer of knowledge. The distinction between codified and tacit scientific knowledge is derived from the various activities that are associated with the production of certified scientific knowledge. The latter is, for the most part, the result of the manipulation of objects to stabilize certain effects in the laboratory. This allows scientists to draw causal connections in the phenomena. The features of the stabilized phenomena, the causal inferences and the characteristics of the final experimental arrangement are the matter of the codified component of that knowledge. The procedures and adjustments that constituted the path before the stable arrangement was achieved are often the stuff of tacit knowledge. At the same time, when manipulation is not possible, the certification of knowledge is also weakened and the results are much more controversial. At this juncture computer simulation makes its entry and allows for 'virtual manipulation' of complex systems grounding a new body of certified knowledge mediated by simulation.

Instrumentation is often mentioned as a significant way in which science and technology interact and, by extension, constitute a linkage between research and industry. Simulators provide a new science-technology relation adding a dimension to the one already established by specialized hardware instruments. Rosenberg has analysed the importance of instrumentation as a way in which science has an economic impact by developing new technology [15, pp.250ff]. In his reflections on the importance of 'upstream' influence of technology on science, he shows how instrumentation provides a significant feedback loop between industry and academic research and mentions the computer as the most significant of these scientific instruments with its general use and widespread impact. He also points out the importance of instrument migration for interdisciplinary collaboration and the mobility of scientists, with the instruments, to other fields.

Simulation would be, in this analysis, a special case of the interaction between science and technology or between research and industry via the computer as a scientific instrument. However, this does not capture important aspects of the role of simulation both in science and in the transfer process. Simulation provides a way to bring the laboratory into the outside world by implementing scientifically derived synthesis and optimization algorithms and inserting them in the production process itself. The interesting thing is that this aspect of knowledge transfer, which is in line with codification, occurs within the bounds of a 'package' that is often accompanied by personnel mobility, signalling technological tacit knowledge. The previous understanding was that the realm of technology was able to achieve functionality *via ad hoc* optimization techniques in areas that lacked the scientific knowledge or ground theory to do it according to a sound scientific model [16, p.144].

The nature of information technology has been mentioned as one of the causes of the growth of networks of innovation [17]. The possibility of rapid exchange of information facilitates the establishment of linkages for technical collaboration. Interestingly, the contemporary emphasis on information technology has promoted the idea that transfer will be facilitated *without* the movement of people. This would go hand in hand with the desire to codify knowledge in order to transfer it more economically with information systems. This case presents an interesting contrast. Software's 'functional coding' could also be considered a causal factor in the patterns of exchange and technology transfer by facilitating rather than replacing certain types of personnel mobility between research, where new knowledge is created, and an industry sector, where most of the economic benefit or impact of that knowledge is reaped.

3.2 *Types of knowledge and the science-technology distinction*

Recent research has emphasized that a proper understanding of the processes of technology transfer between PFRD and industry requires that we go beyond the institutional level to characterize the types of linkages that are formed between PFRD and industry and look at the types of knowledge that are mobilized, manipulated and transferred in them [2,18]. In these studies, the main dimensions of knowledge exchanged in these linkages are three: nature of knowledge along the axis of applied to fundamental; the form of knowledge along the axis of tacit to codified knowledge; and the types of linkages along the axis of informal to formal. These three dimensions are not really orthogonal as can be seen by the common association of tacit and applied knowledge flowing mostly through informal channels. Fundamental research, on the other hand, will strive to produce codified knowledge and may be associated with either type of linkage. The ends of the spectrum are identified with rather stereotypical views of technology, on the one hand, and science on the other. Technology is the realm of applied, tacit knowledge, heavily dependent on informal linkages, while science essentially produces fundamental codified knowledge and is more amenable to formal collaborations.

Authors in the field of science and technology studies have challenged this stereotypical view and suggested that the distinction between science and technology should be dissolved [19]. In spite of this challenge, the distinction has its defenders and is generally incorporated into most economic approaches to the subject [20, p.494,etc.]. In responding to the arguments in STS, Sorensen and Levold [21] maintain that there are reasons why some form of the distinction between science and technology is important. One of these has to do with the different career patterns found in each area and the way they impact the interorganizational relations that are important in innovation. They point out, for example that "the very tacit nature of technological knowledge complicates the transfer of technology and demands mobility of engineers" [21, p.28]. This leads to recruitment policies that "try to hire a new person with this competence before you eventually let someone already employed be trained for the task" [21]. The authors then conclude that one significant difference between science and technology is the way the knowledge is organized in each case. So tacit knowledge is much more important for technology than it is for science. The evidence for this is that in technology "the flow of knowledge must be accompanied by the flow of people" [21, p.30].

The link between personnel mobility and the transfer of technological knowledge has deep historical roots [22, p.5]. However, the case we present in this paper shows that there are significant instances in which this distinction does not hold, such as the software simulators of our case. The mathematical investigations at the core of the research are understood to be basic science. At the same time, they are codified in the form of software and then built into industrial technologies. A flow of people occurs that would indicate the transfer of tacit knowledge. However, the peculiar patterns of this flow that include direct relocation from a basic research to a production setting and reverse flow from chemical plants back to research suggest something else is happening. We suggest in this paper that the software simulator's codified aspect facilitates the recontextualization of people. The simulator codifies the process of adjustment of a chemical plant that an experienced plant manager achieved over a long period of time. The importance of context is still true because the mobility of personnel with the software codification of their research results depends on the structure of the industry they will serve. But the feedback mobility does link the two quite closely. It does resemble the recruitment of a client's employee to learn about the needs of clients, but it differs in that the research is not directly aimed at solving their problems. It enriches a pool of research questions to direct the research in a way that retains its multiple connections with the outside world.

The role of the different types of knowledge in understanding the linkages between PFRD and industry is also demonstrated in the work of Mangematin and Nesta [18]. Building on the work of Cohen and Levinthal [23], they show that firms do not only obtain knowledge to develop new products from such linkages but also expand their capacity to learn and absorb knowledge from external sources. Working with a database of contracts linking private firms to public sector laboratories, they classify the collaborations according to the type of knowledge (fundamental or applied) and its form (codified or tacit) in order to test hypotheses about the capacity of the firm to absorb knowledge from the linkages. They find that a firm's absorptive capacity depends on the particular characteristics of its knowledge base and, especially, on the ability of the firm to exchange several types of knowledge. Low absorptive capacity is also associated with the exchange of only one type of knowledge. Importantly, they also show that when a greater absorption capacity is present the exchanges take place by means of a greater variety of vehicles (articles, reports, instruments, patents, personal contacts, talks and conferences, extended visits by scientists and students).

The case presented in this paper contains a peculiar transfer mechanism with high personnel mobility that seems to be facilitated by a peculiar vehicle which depends on the form of coding involved in software simulation. The contrast with the line of work mentioned above becomes apparent when we point out that, if tacit knowledge exchange is operationalized by tracing personnel mobility, then the movement of persons of our case suggests a high degree of tacit knowledge. At the same time, this is a high impact or high 'spill-over' case with the creation of an intermediate industry sector and significant transformation of the chemical industry. However, in general, a high proportion of tacit knowledge is associated with a low 'spill-over' effect [10, p.905]. The explanation for this anomaly lies in the nature of software simulation that is a hybrid of codified and tacit knowledge providing a vehicle for transfer that enhances the chances of 'spill-over' by enhancing the ability to de-localize its tacit components.

Even when the distinction between science and technology does not depend on the nature of the knowledge involved in each, this case still present some interesting peculiarities. Dasgupta and David [20] distinguish between the communities of science and technology. They maintain that they have different social organizations and, therefore, "the community of Science is concerned with additions to the stock of public knowledge, whereas the community of Technology is concerned with adding to the stream of rents that may be derived from the possession of private knowledge" [20, p.498]. This case still defies that distinction because both goals are legitimately pursued at the same time by the research team.

3.3 *The "Linkage Field" as a long term context for technology transfer*

The assessment of economic impacts of PFRD through knowledge and technology transfer to industry has generally focused on the links that private firms establish with laboratories or research teams [2] or on the formal structures established by public sector institutions to enable collaborations with industry [24,25]. Alternatively, the flow of knowledge through informal contacts or the diffusion of instruments and experimental techniques are included among the ways in which the output of PFRD is constituted as an input to industrial processes of innovation [2, pp.200ff; 15, pp.250ff]. The point of view of industrial firms is important because they are the ones who market new products and realize the economic benefit of knowledge and technology. Undoubtedly, informal channels and serendipitous diffusion paths also play a significant role in knowledge and technology transfer to industry. The resulting aggregate picture, however, is one in which the strategies pursued by those conducting PFRD are almost irrelevant to its economic impact except when they depart from their normal pursuits and accommodate special structures set up for a linkage with industry to take place.

The case presented in this paper certainly does not fit that stereotype. The linkages with industry are multiple and are embedded in a coherent set of relations built over time, which we have termed the 'linkage field' of the research program. Faulkner and Senker have pointed out the diversity in the nature and prospects of the linkages across industry boundaries. For example, they suggest that the close links between PFRD and industry in biotechnology are related to the relative young age of the field, which makes research and industry questions similar [2]. The characteristics of the 'linkage field' in this case are also related to the content of the research activity, especially, by the knowledge and technology flows that are enabled by software simulation. Furthermore, given that simulation techniques can be applied in many different disciplines, the ability to simulate a system of interest to industry creates a dynamic similar to the one detected in biotechnology in any field of inquiry. The software simulation vehicle enables the close coupling that direct relevance of basic research findings produces in the biotechnology industry.

Rosenberg, in his detailed studies of the nature of 'upstream' influences from technology to basic research, has devoted considerable attention to the case of chemical engineering, which underlies our case study. He has pointed out that once a connection between fundamental scientific knowledge and the opportunity for a commercial product based on it has been established, entire new bodies of knowledge may have to be developed in order to reach a commercial scale of production of the new products [15, p.144]. He attributes the emergence of the discipline of chemical engineering to the need to implement large-scale production facilities for chemical processes [15, p.146].

The case in our paper shows a new development in chemical engineering that has moved the field towards basic science research. This has occurred by means of the application of formal mathematical techniques to the synthesis, optimization and control of chemical plants. It has also opened the field to interdisciplinarity because the same mathematical models can be used in fields such as electronics and biotechnology, in which large network systems of mass and energy are important. As a result, the field is able to acquire some autonomy from the specialized concerns of chemical plants and create knowledge propelled by the intellectual interests of its members. It, therefore, acquires the features and incentives of basic research. Then, the nature of software simulation is such that is allows a 'functional coding' of scientific knowledge that brings the basic research activities closer to the actual situation of industrial plants. In this way, it creates a context with greater opportunities for movement of personnel. Software simulation inherently requires a 'functional coding' that translates the skills of the researchers, on the one hand, and of chemical plant operators that produced similar results over a long period of time, on the other. Therefore, research personnel become relevant to the forms needed for supplying industrial clients at the intermediate sector (mainly a specialized software sector) and for the industrial corporations themselves in installing and maintaining the software that controls their plants (control and design).

The mobility of personnel from a research context to industry is generally thought of as a normal outcome of the educational process or a result of the strategy of firms to acquire needed skills. The occurrence of technology transfer by these means is readily recognized [20,21]. However, they are seldom considered as a link between the context of PFRD and industry because they are not seen as a conduit for true two-way communication. Most studies of linkages between firms and universities or national laboratories leading to technology transfer almost universally assume that people are stationary or that they visit the other context for a limited period of time. They basically focus on the communication between people who are staying in each place over the duration of the relevant linkage activities [26]. The linkages are also thought of as relatively short term interactions, which contrasts with the communication that takes place through linkages developed over longer periods of time. This does not necessarily translate in long delays in the transfer of knowledge or technology to industry. The long term linkages allow for the short term transfer that occurs in both directions with the mobility of people who actually change employment. Because of the longer term horizon of the 'linkage field', it is possible to have short term transfer accompanied by people movement who are hired out of one context into another, instead of considering these movements as external to the relation between PFRD and industry. The 'linkage field' provides a broader context for considering the continuous short term or medium term exchanges of both a formal or informal sort.

4 Conclusions

Even though a single case analysis such as this one does not allow strong causal inferences and generalizations, a result from our analysis of a larger number of cases of basic research sponsored by BES does show that software algorithms are a major component in technology transfer from PFRD to industry. It is distinctive because it entails research teams that do not declare a special dedication to industry-related problems or applied science but have a large amount of short term transfer to industry [5]. This case illustrates the role of 'functional coding' of software in technology transfer that may be very significant in a large number of cases and provide a channel for PFRD to have great economic impact. This may occur both by having versions of the algorithms rapidly transferred to industry in products or processes and as a vehicle for the mobility of trained personnel from PFRD to industry. This case also shows that the analysis of linkages between industry and PFRD must account for specialized network structures built over time that sustain a 'linkage field'. This contrasts with the almost universal focus on one-to-one relations governed by contracts or other one-dimensional relations between a PFRD party and a private firm.

The case study presented in this paper suggests that a broader framework is needed for studying linkages between PFRD and industry. Most work in this area is dominated by the stereotype that the inherent culture and incentives of PFRD constitute an obstacle that must be overcome for successful transfer of knowledge to the private sector. This case shows that the PFRD culture and incentives are much more variegated than the stereotype admits and that successful research programs tend to develop linkage fields that provide multiple channels of knowledge and technology transfer. The dynamics of the linkage fields are the appropriate object study, therefore, rather than single point-to-point links between a research project and a company. The analysis of our complete set of case studies presented in a separate paper [27] showed that there are several organizational patterns, termed 'knowledge value alliances', in PFRD with different linkage field dynamics and that any one research program can evolve from one type to another type over time. Each type has peculiar patterns of value creation that ordinary assessment methods do not capture. The case selected in this paper illustrating one striking pattern of linkage field with the peculiarities of software's 'functional coding' shows this, first, in the development of specialized scientific and technological human capital and, second, in the special technology transfer channels via their peculiar career paths.

These results have consequences for R&D managers because their assessment of the impact of the programs they fund must take the value of the linkage fields into account and their management style should explicitly deal with the incentives and disincentives for PIs to develop them. The variety of career paths seems to suggest that students and recent graduates have more reasons to consider participation in research than simply increasing their chances of continuing on an academic track [28]. For the firms, the increasing role of software simulation creates more channels of knowledge acquisition via personnel mobility.

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References

1 Gibbons, M. and Johnson, R. (1974) 'The roles of science in technology innovation', *Research Policy*, Vol. 3, pp.220–242.

2 Faulkner, W. and Senker, J. (1995) *Knowledge Frontiers*, New York, Oxford University Press.

3 Kline, S. and Rosenberg, N. (1986) 'An overview of innovation', in R. Landau and N. Rosenberg (Eds.), *The Positive Sum Strategy*, Washington: National Academy Press.

4 Forrest, J. (1991) 'Models of the process of technological innovation', *Technology Analysis and Strategic Management*, Vol. 3, No. 4, pp.439–453.

5 Bozeman, B., Rogers, J.D., Roessner, J.D. and Klein, H. (1998) *Assessing the Impacts of Basic Research Sponsored by the Office of Basic Energy Sciences: An 'R&D Value Mapping' Approach*, Report to the Office of Basic Energy Sciences, US Department of Energy. Atlanta: School of Public Policy, Georgia Institute of Technology.

6 Pavitt, K. (1991) 'What makes basic research economically useful?', *Research Policy*, Vol. 20, pp.109–119.

7 Rogers, J.D. and Bozeman, B. (1997) 'Basic research and the success of federal lab–industry partnerships', *Journal of Technology Transfer*, Vol. 22, No. 3, pp.37–48.

8 Laredo, P., Mustar, P., Callon, M., Birac, A.M. and Fourest, B. (1992) 'Defining the strategic profile of research labs: the research compass method', in A.F.J. Van Raan, *et al.*, *Science and Technology in a Policy Context*. Leiden: DSWO Press.

9 Crow, M. and Bozeman, B. (1987) 'R&D laboratory classification and public policy: the effects of environmental context on laboratory behavior', *Research Policy*, Vol. 16, pp.229-258.

10 Joly, P.B. and Mangematin, V. (1996) 'Profile of public laboratories, industrial partnerships and organizations of R&D: the dynamics of industrial relationships in a large research organization', *Research Policy*, Vol. 25, No. 9, pp.901–922.

11 Bozeman, B., Dietz, J. and Gaughan, M. (1999) 'Scientific and technical human capital: an alternative approach to R&D evaluation', Presented at the annual meeting of the American Political Science Association, Atlanta, September.

12 US Congress House (1985a) Federal supercomputer programs and policies, Committee on Science and Technology, 99th Congress, No. 44, Hearing June 10, Washington, DC: GPO.

13 Rogers, J.D. (1996) 'The implementation of a national information infrastructure: science and the building of society', unpublished PhD dissertation, Virginia Polytechnic Institute and State University.

14 Rogers, J.D. (1998) 'Internetworking and the politics of science: the role of NSFNET in internet history', *Information Society*, Vol. 14, No. 3, pp.213–228.

15 Rosenberg, N. (1994) *Exploring the Black Box: Technology, Economics, and History*, New York: Cambridge University Press.

16 Rosenberg, N. (1982) *Inside the Black Box: Technology and Economics*, New York: Cambridge University Press.

17 Freeman, C. (1991) 'Networks of innovators: a synthesis of research issues', *Research Policy*, Vol. 20, pp.499–514.

18 Mangematin, V. and Nesta, L. (1999) 'What kind of knowledge can a firm absorb', *International Journal of Technology Management*, Vol. 37, No. 3, pp.149–172.

19 Latour, B. (1987) *Science in Action*, Cambridge: Harvard University Press.

20 Dasgupta, P. and David, P. (1994) 'Towards a new economics of science', *Research Policy*, Vol. 23, No. 5, pp.487–521.

21 Sorensen, K. and Levold, N. (1992) 'Tacit networks, heterogeneous engineers and embodied technology', *Science, Technology and Human Values*, Vol. 17, No. 1, pp.13–35.

22 Hounshell, D. (1984) *From the American System to Mass Production, 1800–1932*, Baltimore, John Hopkins University Press.

23 Cohen, W. and Levinthal, D. (1989) 'Innovation and learning: the two faces of R&D', *Economic Journal*, Vol. 99, pp.569–596.

24 Hameri, A. (1996) 'Technology transfer between basic research and industry', *Technovation*, Vol. 16, No. 2, pp.51–57.

25 Liyanage, S. and Mitchell, H. (1994) 'Strategic management of interactions at the academic industry interface', *Technovation*, Vol. 14, No. 10, pp.641–655.

26 Senker, J. (1993) 'The contribution of tacit knowledge to innovation', *AI & Society*, Vol. 7, pp.208–224.

27 Rogers, J.D. and Bozeman, B. (1999) 'Knowledge value alliances: an alternative to R&D project evaluation', *Science, Technology & Human Values*, forthcoming.

28 Mangematin, V. and Mandran, N. (1998) 'PhD job market: professional trajectories and incentives during the PhD', *Research Policy*, forthcoming.