NANOSPRINT: An Infrastructure for Nanotechnology Foresight

Florin Ciontu

NanoSPRINT, France, florin.ciontu@nanosprint.com

ABSTRACT

NanoSPRINT exploits advances in knowledge engineering to provide a new generation of tools for nanotechnology foresight. Today, the foresight paradigm must cope with new challenges including an increased magnitude of the endeavor undertaken by the scientific community and increasingly complex interactions between the actors influencing the evolution of a scientific field. Nanotechnology accentuates these challenges through some of its specific characteristics: disruptive character and interdisciplinary character. NanoSPRINT's foresight program started as a "from within" effort of the scientific community. NanoSPRINT aims at building a knowledge base incorporating inference capabilities that would empower the researcher in his day-to day endeavor.

Keywords: technological foresight, nanotechnology, knowledge engineering

1 INTRODUCTION

The relationship between society and research is fundamentally grounded in economic reasoning – society funds research and in turn, research provides the means for social progress. Although always existent, this "deal" has become more explicit in recent years through a stronger conditioning of funding on research with a clear if not immediate feed-back to society. Besides becoming more explicit, the "deal" is now implemented through a complex interweaving of interests of practically all the players of the social system: government, industry and civil society.

In light of these changes, the research community is confronted with the challenge of "dreaming pragmatically". Initially, this issue has been tackled through a schism between (1) those at the front-line of technology, with research roadmaps largely determined by the interest of major industrial actors and (2) those preferring to retire to the "ivory tower" of fundamental science. Over the past decade or more, the system has undergone a reform destined to diffuse more homogenously the responsibility of a clear formulation of the feed-back to society.

However, even this status quo is being challenged by fields like nanotechnology whose dynamics are shaped by antagonistic forces: tackling fundamental scientific issues like new molecular structures or manufacturing paradigms under the pressure for results resulting in the spectacular increase in funding of recent years.

In reaction to these types of challenges, the past decades have witnessed the crystallization of the concept of technological foresight and its adoption at the national and corporation-level of decision-making.

The context briefly sketched here outlined the main drivers for the systematic incorporation of foresight at the most basic level of research environment. However, there is a real challenge in adopting a holistic view of scientific, technological and social factors without hampering the creativity of the research process. It is essential that a foresight-centered paradigm transposed at the individual level does not act as a filter but rather as an extension of the scientist's grasp of a cognitive universe of increasing complexity.

This remainder of the paper focuses mainly on the motivational aspects of the NanoSPRINT project and its approach in defining such a paradigm. In Section 2 we discuss few general characteristics of the foresight process from the perspective of emerging challenges. Section 3 focuses on challenges specific to nanotechnology. In Section 4 we sketch a few approaches used to cope with the aforementioned challenges. Section 5 focuses more specifically on the approach adopted in NanoSPRINT's foresight program. Section 6 is dedicated to the final conclusions and the envisioned development of the project.

2 FORESIGHT IN THE KNOWLEDGE ERA

The initial crystallization of the concept of foresight took the form of forecast – a rather simplistic vision of a "unique", predetermined future and a similarly simple goal – predicting that future. The first forecast programs originated in the '50s in the US defense sector. Later on, the concept integrated the notion of forecast into a more complex vision – several scenarios are possible and the evolution according to these scenarios can be influenced by today's decisions.

The champion of integrating forecast/foresight in the technological policy decision making was Japan starting with the '70s. Arguably, this approach contributed to the transition of Japan's position from a producer of cheap, low-quality goods to a technological leader. Over the next two decades, technological foresight has become a crucial component of technological policy decision-making at the national and corporate level. Most "big countries" (US, France, UK, Germany) followed the Japanese model based on extensive Delphi forecasts. Smaller countries like the Netherlands implemented programs relying rather on expert panels. As for the today's vision on foresight, Ben Martin [1] identifies and specifically formulates the continuous, systematic, process-like character (as opposed to a technique-like view) of foresight.

At the corporate level, ~65% of large American companies and more than 82% of very large companies with more than $10bn in sales had forecast programs [2]. Still, at the most basic level, the research group, the process is very informal and relies mostly on the individual's "entrepreneurial" spirit.

The common denominator of today's foresight programs is the overwhelming reliance on communication and networking [2]. The advantage of this approach is that it makes easier to extract undocumented tacit knowledge. Its cons, poor reuse of the effort, poor scalability with respect to the increasing complexity and poor standardization of the process at the individual level, are an obvious consequence of the "handcraft" character.

Moreover, significant challenges emerge in today's environment, ranging from the magnitude of the technological endeavors undertaken by the scientific community to the increasingly complex interactions between the players active around a technological field.

The accelerated rate of disruptive technologies is the biggest contributor to the first complexity source. This challenges the grounds of one of the previously well-established hypotheses of foresight: products within a given industry depend on a finite number of technologies and components and the foresight problem can be shifted at the level of each of these technologies. The second factor is the obvious increase in R&D cycles in both time and money.

The players' level is currently undergoing a major shift towards the triple-helix model of interaction between government-research-industry introduced in [3]. The model could be furthermore extended to include other components like the civil society (e.g. the role of non-governmental agencies in the generically modified organisms).

2. CHALLENGES FOR NANOTECHNOLOGY FORESIGHT

All the aforementioned challenges find a direct instantiation in the case of nanotechnology and are reinforced by the considerable magnitude of the two forces shaping the dynamics of the field. First, nanotechnology involves a considerable amount of tackling fundamental scientific issues like new molecular structures or manufacturing paradigms (e.g. self-assembly). Despite an undisputable disruptive potential these issues have natural fuzziness in terms of evolution and outcomes. Secondly, as of 2004, it has become a $3bn public funding issue – more than enough to require a level of pragmatism from which research dealing with fundamental issues was traditionally spared. These two forces have antagonistic components that are intrinsically difficult to reconcile.

Moreover, the fact that the research spectrum of nanotechnology spans from fundamental research to applications leads to a layered evolution of different trends. This evolution can be structured on three successive waves: instrumentation, nanostructures and applications. Instrumentation companies selling tools to pursue nanotech R&D (e.g. selling Atomic Force Microscopes) are entering currently a low growth phase as most labs have been equipped. The big question is whether this industry will evolve into an industry similar to the semiconductor equipment one but this in turn depends on the emergence of large-volume applications. Companies focusing on the fabrication of nanostructures (raw materials, the basic bricks) are booming with one common objective: delaying mass production solutions. With costs scaling down two orders/year in some cases (carbon nanotubes), the common target is to make costs competitive within 5 years. Finally, the momentum for applications is slowly developing with an increasing number of start-ups appearing each year. At the same time, more and more big companies commit R&D budgets to nanotech. However, the applications segment will enter the high-growth slope of the S-curve in 5-10 years. The central message of this picture is the correlation between the evolutions of different areas of nanotechnology which renders imprecise predictions based on data from focused segments.

An anatomy of a nanotech subfield, carbon nanotubes, is particularly relevant for this discussion. Discovered in 1991 "by accident", carbon nanotubes [7] are molecular level nanostructures with remarkable properties. They are 100 times stiffer than steel for a sixth of the weight, they are very good electrical and thermal conductors and can be used as field emitters. However, interest in the field literally exploded only at the end of the '90 when synthesis methods lowered the production costs of carbon nanotubes enough to allow experiments in laboratories without any experience in their synthesis. At this point the maturity (due to development in the '80s) and large scale diffusion of instrumentation with atomic resolution facilitated the explorations of the remarkable properties mentioned above. With around 44 commercial providers currently focusing on scalable production methods and costs going down at an exponential rate, carbon nanotubes are one of the components with the strongest potential for real-life applications. Although extensive research on applications of nanotubes is on going, it will probably take longer than 5 years to see the cost of nanotubes scaled down to economically competitive levels and incorporated in commercial applications. This example illustrates the fact that in addition to the inter-layer dependency mentioned above, each vertical segment has its own S-curve.

Among the extra-technological factors, the presence of government is particularly strong in nanotechnology and not only though the traditional vehicle of funding research. Governmental support targets are not only universities but also venture capital and small firms. Additionally governmental organizations are particularly active in intermediating interactions between the universities, industry and the general public.

Finally, non-governmental organizations are expected to play a particularly important role. Although nanotechnology is in an incipient phase there are already ethical and environmental concerns. And even if, for instance, the potential toxicity of carbon nanotubes is considered very seriously through studies of specific problems [8],[9] various factors like the popular press [10],[11] can bring in a serious amount of unpredictability .

3 COPING WITH CHALLENGES

A generic solution to tackling complexity consists of shifting the decision process at the level of patterns. However, a practical foresight approach based on this principle requires being able to derive these patterns automatically. Moreover, the content from which the patterns would be extracted should cover technological as well as socio-economic data and be obtainable through concurrent gathering of disparate information units. Finally, irrespective of the degree of automation, the workflow should include verification and checking mechanisms.

Whether these desiderata are fully attainable or not could be a matter of interminable debates. Instead, we prefer to focus on a few instances where at least partial success has been demonstrated.

A very illustrative example for pattern extraction from technological data is TRIZ [11] (a Russian acronym for a Theory of Inventive Problem Solving). This methodology evolved from extensive studies of technical and patent information and consists of a set of principles that are applied in different forms in the innovation process. Although the penetration of TRIZ has been relatively slow, more and more success stories have been documented in recent years including Samsung hiring six TRIZ specialists from the former URSS for 18 months and accounting for $91 million in direct benefits. As of today, the TRIZ users-list includes companies like General Motors, Ford, IBM, Samsung, Motorola, Boeing etc. An example of foresight approach based on TRIZ is provided in [12]. Besides methodologies like TRIZ, some tools try to tackle (e.g. [13]) the complexity issue by extracting statistical correlations from technical data like patents. However, their impact is relatively limited and they have little predictive value.

As mentioned in the our previous brief analysis of the challenges of the foresight process, no pertinent foresight program can be implemented without taking into account the interactions between technological and non-technological factors (sociological, political etc.). From the perspective of pattern extraction, Eleonor Glor's work [14] is a good example (though many others could be listed here), where sociological factors ranging from individual motivation to organizational culture and the challenge environment are systematically taken into account in order to derive conclusions on creativity, implementation and the outcome of innovation.

A common characteristic of the cases mentioned here is their lack of formal character. By consequence, their results range from qualitative observations to at best an empirical approach. TRIZ for instance is far from a formal science and integrating it is a very subjective experience which translates into some of the trainees loving it while others find it sterile. A step forward is made by products [14] which combine syntactic and text search with elements of TRIZ.

Perhaps not surprisingly, the most audacious approach in coping with the challenges of an increased complexity through a **systematic approach** comes from the US defense sector. DARPA's High Performance Knowledge Bases (HPKB) [4] project was the first program destined to build on recent advances in Knowledge Representation and Reasoning [5] in order to create a new generation of tools for foresight. Test problems included crisis management and battle space related problems. The final conclusion of this $36 million effort was that KRR are mature enough to be considered for applications but the cost of encoding knowledge was prohibitive. The Rapid Knowledge Formation (RFK) [6] program focused on developing methodologies and tools designed to scale down the cost of encoding knowledge in databases. More precisely, the objective of this program was to empower subject matter knowledge experts without prior training in AI to encode information. The results of the project confirm the ability of subject matter experts with minimal AI training (2-3 weeks) to encode knowledge with results comparable to the ones obtained by Knowledge Engineers.

The use of knowledge engineering techniques in the two DARPA projects mentioned above, with the specific goal of coping with complexity in the foresight process and the results are particularly encouraging for the approach we envision for the NanoSPRINT project.

4 NANOSPRINT

NanoSPRINT's foresight program builds on the experience accumulated by TIMA Labs (http://tima.imag.fr) in dealing with successive technological waves in a strong interaction with industry, other laboratories or governmental agencies. Our approach tackles the challenges discussed at the beginning of this paper through a “from within” effort of the research community to systematically integrate foresight into the researcher’s work approach. Simultaneously, the project aims at providing the tools to bridge the knowledge gap between players involved in the development of nanotechnology and players from outside the nanotech world.

The latter category covers (1) decision makers from traditional industries (2) research & development engineers (3) students and (4) the general public. In order to bridge this gap, NanoSPRINT provides the tools to store knowledge on nanotechnology and to extract custom information on an on-demand basis.

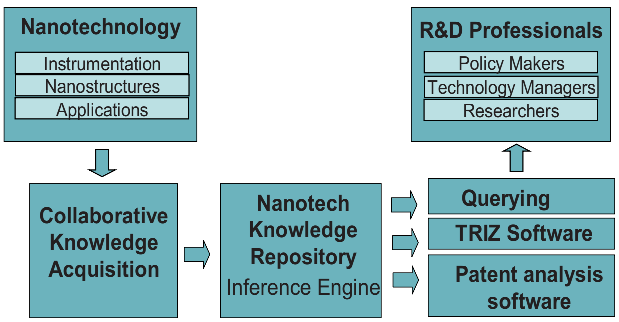

Figure 1: NanoSPRINT bridges the knowledge gap between nanotech players and players from traditional industries. Using a knowledge engineering centered approach.

NanoSPRINT’s approach is centered around a Nanotechnology Knowledge Repository that (1) stores facts and meta-knowledge on nanotechnology and (2) (semi)-automatically derives answers to new questions based on stored facts.

The server is integrated in the following flow:

1. Knowledge is acquired from multiple sources by scientific analysts and encoded into a knowledge database. For example, the formalisms used to encode knowledge could use notions like: (1) concepts, (2) instances of the concepts, (3) rules and (4) axioms (which are equivalent to assertions or real-world facts). At this point, knowledge is expressed in a formal manner.

2. A reasoning server uses this “formalized” knowledge to infer answers to new questions that require knowledge which is not available immediately in the encoded texts. Using these mechanisms, knowledge is generated based on tractable implementations of subsets of the first-order logic.

3. Users access this knowledge by (1) browsing a content structure or, more importantly, (2) through specific questions. As the current state of Natural Language Processing does not allow free querying, current efforts are directed towards the development of graphical query interfaces.

The workflow presented here is oriented towards automation at each of its stages: from data gathering to decision-making. However, inherent problems arising from fundamental limitations (e.g. determining if a query results from a knowledge base is not decidable) will require extensive testing and human supervision before application to real-life issues.

5 CONCLUSIONS

This quick review of foresight from the perspective of emerging challenges was designed as a motivational paper for the need for a new approach making use of recent advances in knowledge representation and reasoning. The flow sketched here delineates some clear stages: knowledge acquisition, reasoning paradigm as well as issues related to the interface with the end-user. At each stage there are still many issues that remain to be solved in order to make economically feasible the application of this paradigm. Ongoing work at TIMA Laboratory, tackles this issue through a Pilot Project focusing on carbon nanotubes. Aside from presenting our motivations, this paper constitutes an open invitation to the carbon-nanotubes community to participate in this endeavor.

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