



## Scripting possible futures of nanotechnologies: A methodology that enhances reflexivity

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### A B S T R A C T

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Nanoscience is full of promises. However, these promises often do not take into account the realities of product development and the limited coupling with scientific research. On the basis of literature and earlier projects, we have developed a mapping methodology (“bridging gaps in the innovation chain”) and explored it for a particular case, scanning tunnelling microscopy in the liquid phase with two possible applications. The methodology can be used instrumentally, to improve valorisation of scientific research, but also reflexively, to enable scientists (particularly junior scientists) to gain a better understanding of the possible societal contexts of their work.

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### 1. Introduction

Nanotechnology is surrounded by promises, from grandiose visions about human enhancement and a third industrial revolution, to more pedestrian but nevertheless important expectations about improving a coating or creating a better/cheaper fuel cell. Such promises are important for mobilising resources, both financial and symbolic (political). There are also the risks of hype and ensuing disappointment [1].

The promises can be referred to by nano-researchers in their research proposals and presentations, and may then become more specific. However, in general the promises of nanotechnology are like an aura around ongoing research rather than that there are actual connections made with applications and uptake in society. This, of course, depends on the location of the researcher. In a public research institute devoted to applied and strategic research, connections are being made, and there are networks in place. In universities, the situation is different. While there are now university-based research centres that combine ‘excellence’ and ‘relevance’ [2], applications are far removed from the researcher at the workbench, and particularly for junior researchers (Ph.D. students, postdocs).

This is a challenge, and we believe it is important to explore potential research connections even when they are not (yet) linked to applications. We see this as a way to increase the reflexivity of nanoscientists, in particular junior scientists, about present and future societal contexts of their work, by mapping and evaluating possible linkages rather than just referring to a broadly formulated promise. Such a mapping approach can also help to improve the valorisation of university research.

Such reflexivity is important in general, but definitely so for nanoscientists and engineers. There is an asymmetry: on the one hand, concern about the general public’s lack of awareness and understanding of nanoscience and technology [3,4], but on the other hand, no concern about the limited understanding of society on the part of nanoscientists and engineers. Of course, these scientists and engineers need not become social scientists, but they might become more knowledgeable about relevant tools and insights.

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This is what we want to contribute to in our research project: elaborate a methodology to turn open-ended promises into concrete challenges. At the same time, the project is an attempt at reflexivity-in-action. Our mapping methodology was inspired by the idea of ‘future scripts’ [5,6], which we specified as a possible future innovation value chain that could take up and realize the potential of some nanoscience research. Comparison with the present situation then allows identification of gaps and barriers in the present networks. Such a scripting exercise can be done in considerable detail, including checks and counterchecks with various relevant actors. This is necessary if it is to provide support for strategic choices and robust action. For the task of increasing reflexivity, an exploratory version will be sufficient, particularly if the exploration is conducted by the nanoscientist himself or herself (who will have little time to spare anyway). In this article, we outline the methodology and offer findings from our exploration, including an evaluation of the ways reflexivity is enhanced.

**2. Mapping methodology**

There are always gaps in actual, and certainly in projected, innovation value chains; these are bridged by global expectations (promises) and projections of what others might do to realize them. Such bridging is reflected in (and actually part of) what is called strategic research. Strategic research is basic research carried out with the expectation that it will produce a broad base of knowledge likely to form the background to the solution of recognized current or future practical problems [7].

Promises can remain empty hand-waving. There might be attempts to check the extent of the emptiness by asking “how realistic is this promise?” Our mapping methodology translates the question of being realistic into a more productive question about present and future value chains, and where nano is going to insert itself. (A similar double question, in terms of present and future networks, was studied in the SocRobust project [8].)

In order to specify an innovation value chain, we started with a sophisticated model of innovation, the Chain-Link model [9,10], which is shown in Fig. 1. In our version, however, we not only look at the intra-organisational innovation chain, but add inter-organisational links and so-called framework conditions—external contexts and structures, like regulation, that are not directly involved with the creation or application of knowledge but do influence what happens.

Key points of the chain-link model are the forward and backward interactions along the chain, and the notion of research as delivering to a knowledge reservoir on which other actors can draw, rather than being part of a linear chain from invention to innovation to (hopefully) market success. The framework conditions are relevant for what happens in the innovation chain (e.g., patent regulation frameworks), but also for embedding in society [11]. Our extended model is also informed by Abernathy and Clark’s 1985 approach [12], where they map innovations along two dimensions: (1) as requiring few or many new competencies and capabilities within the organisations, and (2) having few or many new customer, market, and user linkages. Thus, the scripting exercise should include an assessment of the need for new capabilities in companies and other organisations and for new links between actors, also checking whether and where new actors are emerging in the networks.

The next step is to distinguish between the present innovation value chains, networks, and frame conditions, and the potential future chains, networks, and frame conditions. We use the notion of fictive script [6]: what should be in place in order for the envisaged innovation actually to occur and be successful? One can ask knowledgeable actors about their

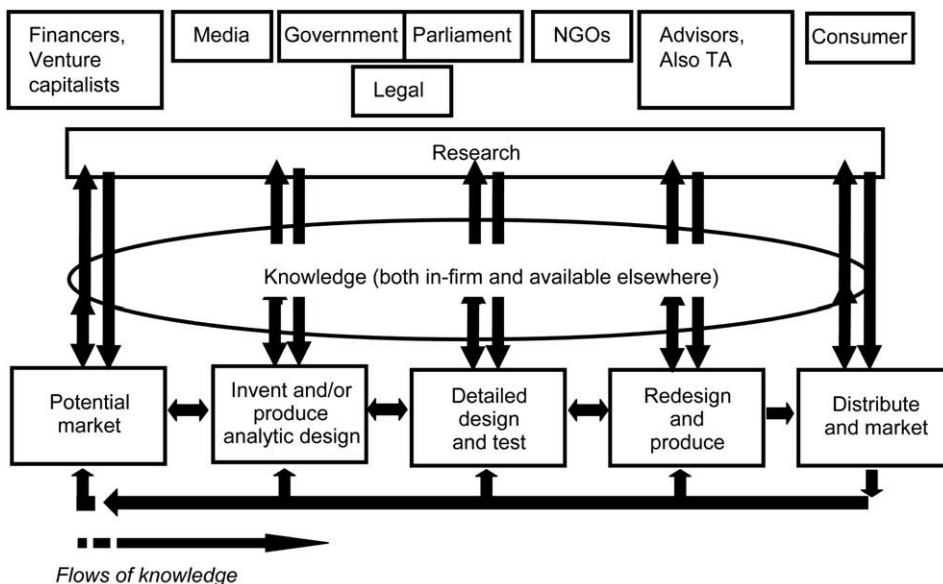


Fig. 1. Chain link model (Phillips 2003 [10]), with additional framework conditions.

assessment, preferably actors from different parts of the network, in order to avoid one-sided (i.e., concentric) views. The analyst can speculate about this as well, and will have to do so in order to identify important actors and interactions.

Comparisons between the two maps allow identification of gaps in the present network, and sometimes also dynamics that are necessary to achieve what was envisaged. Even when such an exercise is done in an exploratory fashion, conclusions are already possible that enable the broadening of the view of the project managers concerned [8], and in our case, allow nanoscientists to entertain a broader view of the context in which their work is done.

### 3. Research design

Since our main goal was to explore this mapping method as a way of enhancing the reflexivity of nanoscientists, we focused on the area of nanoscience in which author denBoer (DdB) is working—scanning tunnelling microscopy (STM) in the liquid phase [13]. This is an area of fundamental research that attempts to extend the use of STM from solids in vacuum to measurements in the liquid phase. Applications are not foreseen, or at least, are not the driving force.

The basic principle of STM is visualized in Fig. 2. We will not go into details here except to note that the charge transfer between the tip and the surface being traced measures the height of details of the surface, but can also be used in the other direction, to modify what is on that surface. This is the physical principle for one of the applications that will be discussed.

We will lay out the different steps of our scripting exercise in some detail, so as to enable other (nano)scientists to do similar exercises.

The first step involved choosing possible applications that could be mapped. A gross list was developed, mainly based on brainstorming discussions within the research group at Radboud University in which DdB's work was located. This, as well as further discussion as to which two cases to choose, stimulated the reflexivity of members of the research group as a side effect of the exercise. The cases eventually chosen—synthesis of exotic molecules based on active use of the tip, and drug development—had different expected innovation value chains, a contrast that would facilitate broader interpretation. In particular, we expected most of the innovation value chain for drug development to be already in place (it is a case of substitution for an existing function), while synthesis of exotic molecules would require new capabilities and linkages.

The second part of the research included document analysis and checks to identify what would be important for the innovation value chain network around each of the two possible applications. This sketch of the future innovation value chain network was the basis for selecting actors to be interviewed. We selected a limited number—five for the first application and six for the second application—which partly overlapped when framing conditions were the topic (see Appendix 1 for the list). This limited number reflected time limitations on DdB, but also on nanoscientists more generally. We wanted to be realistic; a nanoscientist cannot be expected to invest a lot of time in fully fledged social science research of the possible innovation value chains and networks.

In the third part of the research, an interview instrument was developed, which consisted of fictive script questions followed by envisaged linkages and network questions. By way of intermezzo, there was a question about desirability. Then the draft innovation value chain and network was shown, and the interviewee was asked to comment and perhaps add. See Appendix 2 for the outline of the interview instrument.

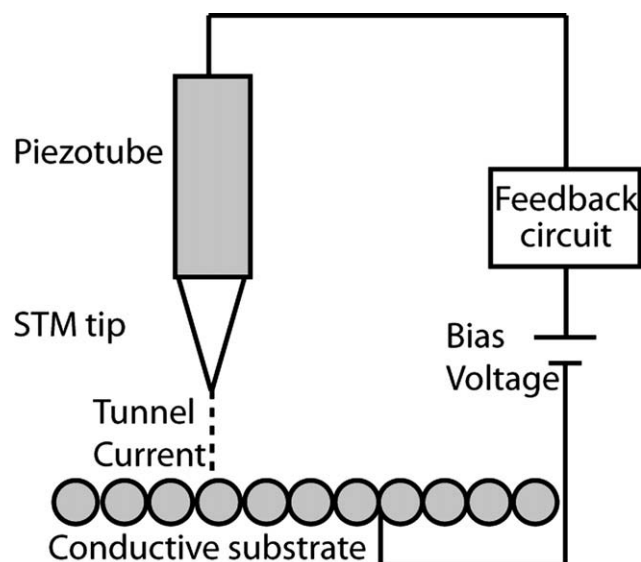


Fig. 2. Basic set-up of scanning tunnelling microscopy.

The fourth part of the research involved analysis of the data with added reflection on the scope of the project as potentially enhancing reflexivity.

In the following, we present the results from the two cases, together with some comments made by interviewees. Some comparisons are made in the last section of the paper, where we also offer reflections on ways to enhance reflexivity.

#### 4. Case 1: exotic molecule production

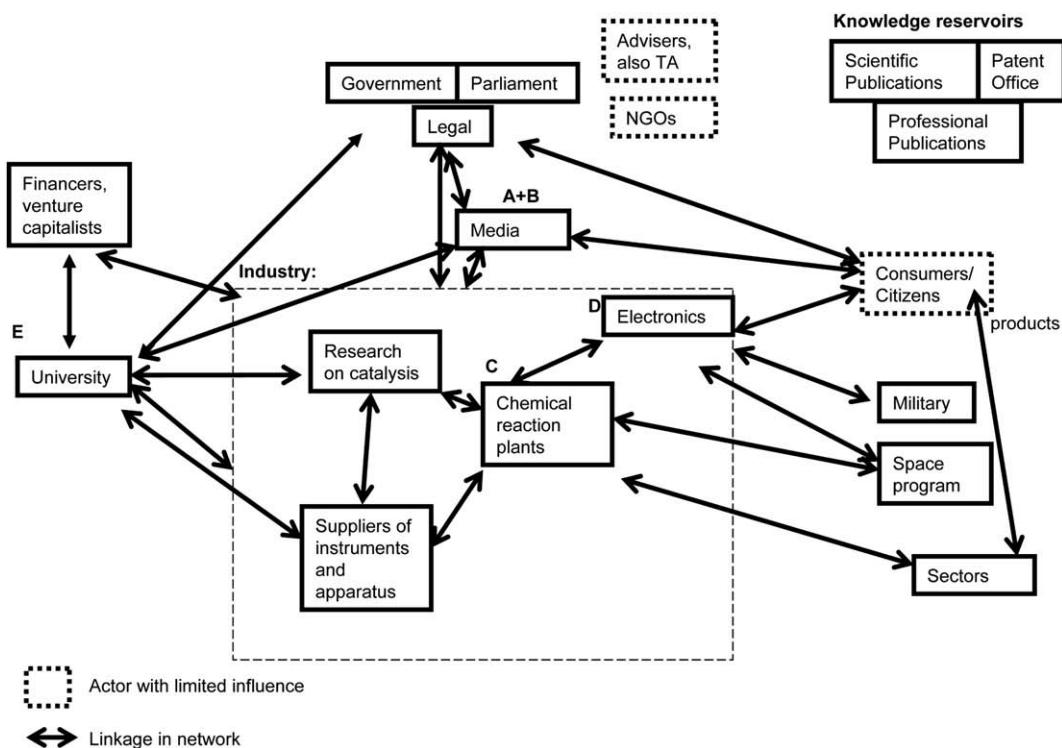
Scanning tunnelling microscopy, while mainly used for imaging, also enables manipulation. This feature can be exploited to produce exotic molecules by coupling smaller molecules together. The STM tip is immersed in a solution and sends a current to part of a molecule lying on the surface. This part is made more reactive so that another molecule can attach there. Since it is difficult to produce large quantities this way, the application is limited to molecules that cannot be produced with regular chemical means and are to be used in small quantities only—thus, exotic molecules.

A competing technology for the production of exotic molecules is biotechnology using selected and/or genetically modified micro-organisms for synthesis. In that case, one depends on what their metabolism can deliver. As a production, it is in place and the network is already well developed. STM-based production would have the best chance, at least in the beginning, when going for molecules that cannot be produced biotechnologically. Then the technological niche for its development can be linked to a market niche [14], if there is sufficient demand for such molecules, as might be the case in the space sector.

The technological feasibility, however, was judged by most of the interviewees as poor, especially in terms of obtaining performance levels that had commercial value. While some interviewees felt that the capacity to use STM to synthesize molecules might be in place in about 10 years, the general opinion was that it would not leave the lab environment due to competing technologies that do better. Interviewees A and B, both from media, were generally sceptical about nanoscience and technology R&D, which they believe “promises much, but delivers very little”, and they argued that STM production would not be possible at all.

##### 4.1. Fictive script mapping

Chemical synthesis is versatile (“almost an art-form,” said interviewee E) and there are established suppliers on the market for specialized molecules. The capacity to make a large quantity of molecules in one batch and at relatively low cost is



**Fig. 3.** Existing innovation value chain and network for chemical synthesis of special molecules. Capital letters in the diagram indicate the position of the interviewees.

an important asset. STM production will have to insert itself into the innovation value chain and networks and build on their projected capacity to create molecules that are otherwise difficult to synthesize.

Fig. 3 depicts the innovation value chain in context. Linkages between types of actors indicate interactions (flows, influence, anticipations). Many linkages are general, such as universities delivering graduates, or consumers/citizens making buying decisions and voting. Actors and activities in the box, as well as their linkages, are drawn based on our interviews. The separate specification of military and space sectors anticipates their importance for STM-based synthesis of exotic molecules (see Fig. 4). Compared with Fig. 1, knowledge reservoirs are now positioned as part of the context, reflecting the fact that they are not limited to knowledge that is directly relevant to chemical synthesis, and that information is drawn from them in various ways by different actors. (Note: linkages with other parts of the diagram are not shown here.) Of course, types of actors, sectors, and linkages can be further specified (see, for example, [8]), but this informal version suffices for our present purpose.

For STM in the liquid phase to be used for commercial chemical synthesis, product–market combinations have to be identified. In the interviews, three options were posed:

1. Customers needing only a small amount of molecules, where performance is more important than cost, e.g., highly pure optical materials in the space sector.
2. The field of molecular electronics, where complex molecules are used to form the active components on a chip. Having specific molecules at specific spots could be important, in which case the resolution that STM allows would be of help. Another possibility is “writing” a circuit with the STM tip, thus changing the electronic characteristics of a specific molecule. Interviewee D from Philips (an electronics and consumer products firm) said they might use this technology since it fits their range of products and their know-how, as well as know-how in the semiconductor industry.
3. Catalysts, especially enzyme-like catalysts, most likely made by modifying already existing enzymes. These catalysts would have to be very efficient to compensate for the cost of production and application.

In Fig. 4, the central box depicts (informally) the required changes, i.e., new capabilities, new linkages. Our interviewees emphasized the importance of universities as the place where “proof of principle” is developed. A technology platform that

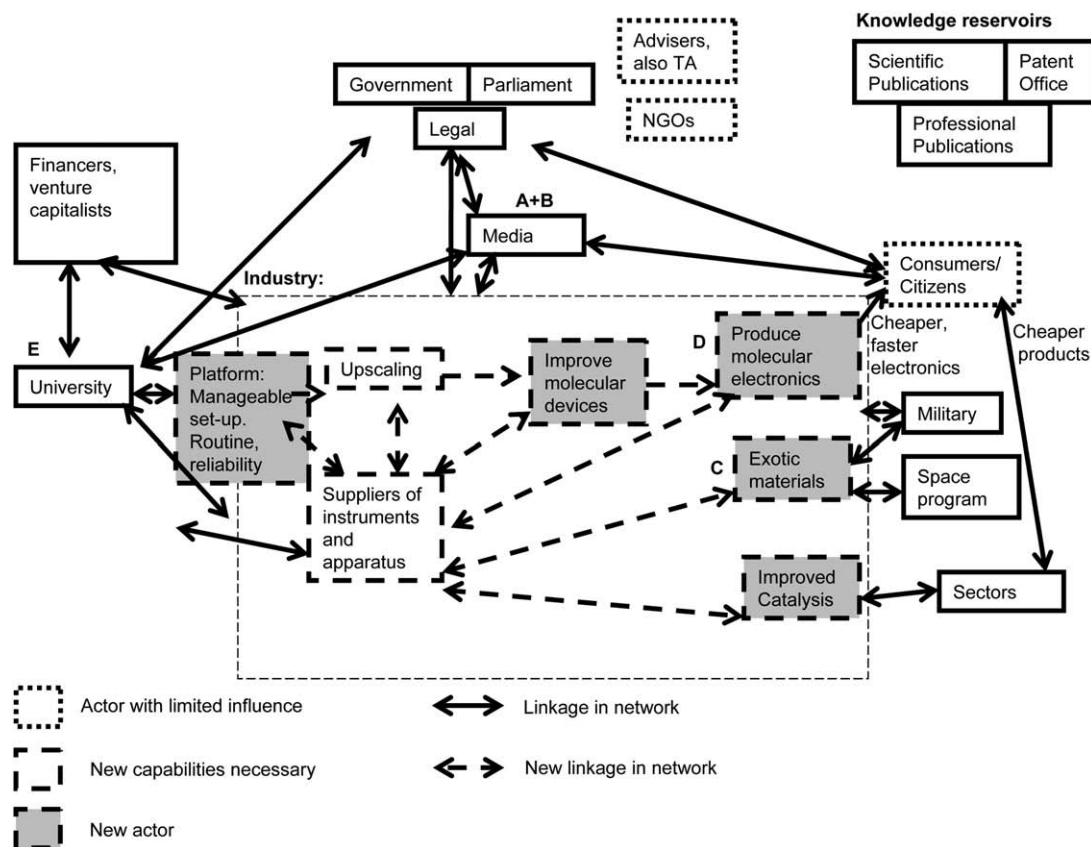


Fig. 4. Requirements for the innovation value chain and network for STM-based synthesis of special molecules. Capital letters in the diagram indicate the position of the interviewees.

bridges the gap between university and industry turns a laboratory prototype into a range of working devices [15]. This further step was also seen as the responsibility of the university.

The next link in the chain could be a spin-off company, or collaboration between a large firm and university. It is an open question whether established suppliers of chemicals will invest in such developments. In any case, there is a market opportunity for the suppliers of STM and other relevant instruments, and they may take the lead. Linkages with molecular electronics, with users of exotic materials (space, military), and with sectors interested in dedicated catalysts have to be built up. This will require dedicated further development of the molecular devices. Companies like Philips will consider the necessary capacity building to do so, or it could decide there would be insufficient return on such an investment. Given the importance of business-to-business linkages and interactions with professional customers, the media will play a minor role unless they believe that the notion of 'exotic molecules' might capture the interest of their readers and listeners. However, the ensuing hype, while facilitating resource mobilisation at first, may ultimately lead to disappointment and retraction of support.

Considering the overall picture, there is a further challenge: the requirements of the future script in various parts of the innovation value chain and linkages with sectors of use, have to be in place together to make STM-based synthesis of exotic molecules a going concern. This requires concertation by a leading actor or a coalition of actors.

## 5. Case 2: drug development

In this case, the technical starting point is that STM can image a surface using molecular resolution. These surfaces can be synthetic membranes that mimic the cell surface or parts of a real membrane. Then the active component of a drug could be imaged while it attaches to the receptors. Doing this in the liquid phase, preferably liquids that contain ions/salts as in the human body, would constitute a test system for drugs. This application was considered to be a useful and realistic use of the STM technology because it stays quite close to what a scanning tunnelling microscope is used for today.

### 5.1. Fictive script mapping

The innovation network of drug development, testing, and production already exists (see Fig. 5). Before drugs come to the market, a lot of pre-clinical and clinical testing is required. Testing is done in-house, or by specialized companies, or in hospitals. In the R&D phase, suppliers of test equipment play a role. The European Agency for the Evaluation of Medicinal Products (EMA) has an oversight function, develops technical guidance, and provides scientific advice for the regulation of drugs (in the U.S., this is the Federal Drug Administration, a regulatory agency, in the diagram).

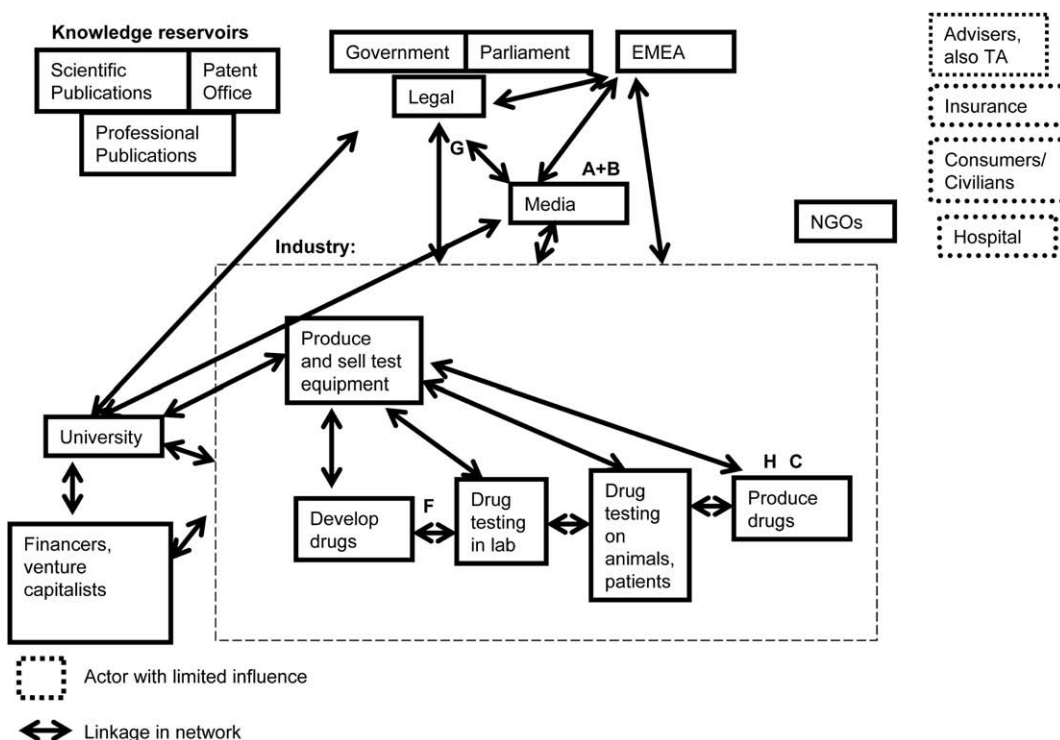


Fig. 5. Present innovation value chain and network for drug development and testing. Capital letters in the diagram indicate the position of the interviewees.

The STM-based application can be inserted into the innovation value chain without the need for new linkages. However, it is necessary for the relevant companies to obtain new skills. First, the application has to be developed from proof of principle (often, in a university) with some promising applications. At first, cooperation between university and industry will probably be important. Interviewees differed about routing, suggesting possibly through a supplier of devices (perhaps a start-up company) or through a large pharmaceutical firm. Interviewee F, from a pharmaceutical company, suggested that pharmaceutical companies will wait for start-ups or spin-offs to do the risky work, and then absorb them when they become successful. They might also be absorbed by a large company that supplies to the pharmaceutical world, such as a spectroscopy firm. Interviewee B, the editor of a professional chemistry magazine, did not have much confidence in any routes through small firms.

In a second phase, when the application becomes commercially available, again there were different assessments. In interviewee B's view, the technique is complex, and there must be a dedicated company to support drug development. Interviewee F agreed, citing the need for specialist operations. Other interviewees (C and H) expected the pharmaceutical companies to purchase their own devices and get the necessary skills in-house. Interviewee H went so far as to claim that the device could be used in many places, including universities and academic hospitals.

The cost of the device is, of course, a critical factor. A common perception was that this technique would not be used by small companies that produce generic drugs. General issues of in-house versus outsourcing were apparent in the interviews, as well as the complexity of a technology and the need for specialist skills. Economists and innovation scholars have been studying these questions without arriving at final answers. Actors from varying backgrounds draw on their experiences and come up with the same issues without being able to resolve them.

One aspect of this application of the STM technique that might prove crucial is the link with animal testing. The interest in this direction is reflected in meetings like the conference organized by the Institute of Nanotechnology on nanotechnology alternatives to animal experiments [16]. The STM technique has the potential to partially replace animal testing, according to interviewee F, provided it can be shown to be stable enough and to accurately predict relevant characteristics of a drug. EMEA can play a key role. If it is convinced that the method can be used reliably, it might require this testing technique to be performed on every new drug. Interviewee H, on the other hand, did not think the STM-based technique would replace animal testing because alternative approaches, in particular use of cell lines, would be far more convenient.

Fig. 6 indicates what is necessary for the STM-based technique to be developed and implemented. It confirms our idea that it amounts to “local” insertion in the innovation value chain, with no major changes.

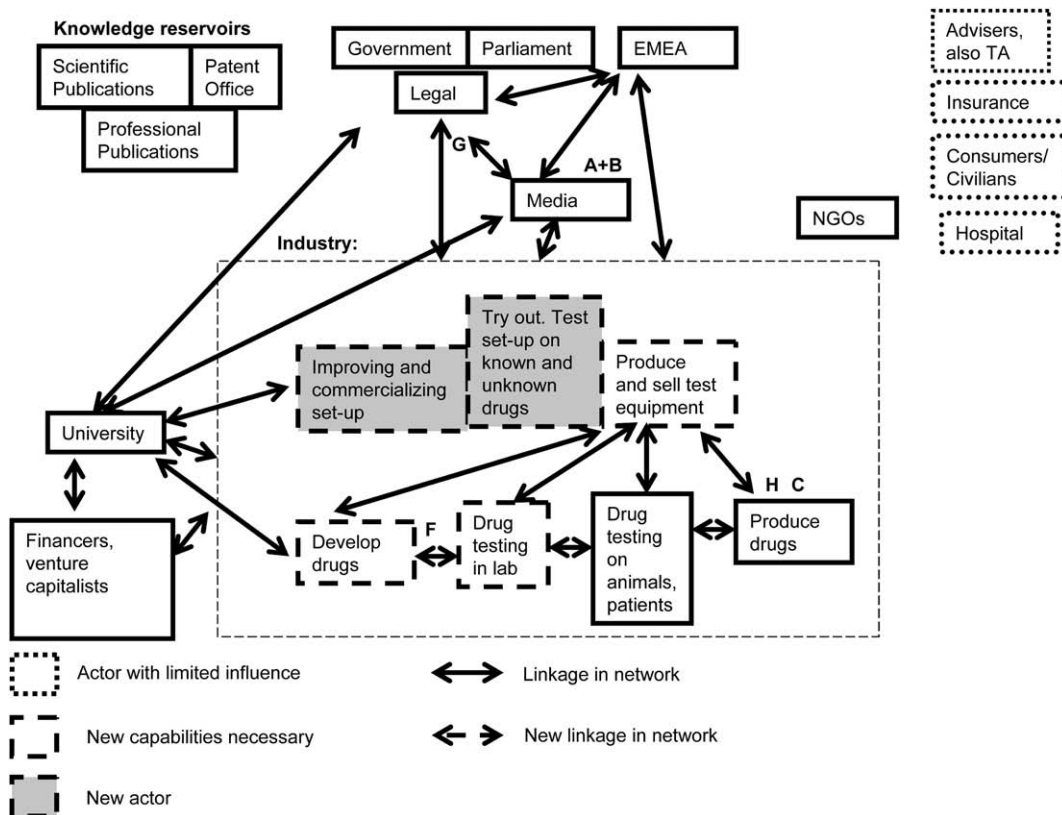


Fig. 6. Future innovation value chain and network for drug development and STM-based testing. Capital letters in the diagram indicate the position of the interviewees.

## 6. Conclusion

Three types of conclusions are in order: one on the findings about the innovation value chains and networks, another on the methodology itself (which might be developed further and applied systematically), and a third on the question of broadening of views and enhancing reflexivity.

Our expectation that the two cases provided here would show different dynamics because of the different starting points (little fit of the application to the existing network) was confirmed. Technically, both applications are still speculations inspired by basic research with yet no proof of principle. In addition, the techniques are and will probably remain complex and demanding. Thus, dedicated firms will be important. For synthesis of exotic molecules, there might be some routinisation of technological platforms. For drug development support, there will be more variety. Further, other parties than regular market actors will be important, especially with regard to the issue of animal experiments.

In both cases, our interviewees were eager to discuss the role of universities, and almost all of them gave universities an important role in the early stages. They also emphasized the importance of university-industry collaborations, even if they had different views on appropriate routings.

In the maps we offered, there were more details than we discussed in the main text. These derived from our study of the literature, relevant documents for the two cases, and informal conversations. For our present purpose—to show the potential of this approach to obtain a broader view of the context in which applications of fundamental research might develop, and to do so with limited effort—the presentation of our main findings is sufficient.

The approach appears to be promising more generally. It can support strategy articulation of a variety of actors (not just firms), and allow broader technology assessment than is usually done, even if there is recognition of the need for broadening (see, for example [17]). By now, there are a number of such approaches, all of which draw on understanding the complex dynamics of technological developments and their embedding in society in order to anticipate and improve decisions and choices in the present [8,18].

In its present form, a weakness of the approach for supporting decision making (for enhancing reflexivity, the situation is different) is its reliance on interviews and informal communication with relevant actors. This produces soft data. We treated interviewees as experts about future developments, which they clearly cannot be, even if some have articulate insights. They fall back on their own experiences and convictions (up to bias), as was sometimes visible in their responses. Furthermore, their view of what is feasible may be colored by their being embedded in present networks, which might be a reason why synthesis of exotic molecules was considered to be less feasible than support for drug development. Interview data has to be complemented by document analysis and dedicated data gathering and analysis, whenever possible.

A further improvement of, or at least addition to, the approach is the use of interactive workshops with relevant actors, supported by sociotechnical scenarios. There is some experience now for a few areas of nanoscience and technology [19–21].

In this exploratory study there was no systematic attempt to measure enhanced reflexivity. We did profit from general considerations [22], and a few recent qualitative studies [23]. We can report on what happened, though, and reflect on it. The reflexivity induced by our project took place at different levels. The PhD student (DdB) became more reflexive by doing this project, performing socio-technological research and obtaining interviewing skills. An additional stimulus was participation in social science seminars and meetings where social studies of nanoscience were discussed.

The research group of which DdB was part, was influenced by the fact that this research was pursued. They were included in the beginning in the discussion about possible applications. Even though at first the group was rather hesitant and wondered what the use of this research might be, the group members became more interested later on. However, similar to what Erik Fisher [23] found in his study at the University of Colorado (Boulder), our research group members were hesitant to participate or to start this kind of project themselves. Interestingly, as the research progressed, the group's attitude shifted. Members could come to DdB with questions that were more or less related to the innovation study, and later on, questions about nanotechnology in society (like risk issues and public perception) that had nothing to do with the specific research project.

A further type of reflexivity derives from the fact that this study was conducted by a nanoscience Ph.D. student who is part of a “flagship” (led by author SS) in the Dutch NanoNed R&D consortium (see [www.nanoned.nl](http://www.nanoned.nl)). This drew the attention of nanoscientists and technologists as well as observers of nanotechnology, by indicating that nanoscientists need not be limited to doing only nanoscience. It was shown to be another form of building bridges between nanotechnology and society in addition to studies of ethical, legal, and social aspects by social scientists [24] and societal debate [25]. This project, and its being part of a nanoscience Ph.D. (thus, a Ph.D.+), is a “proof of principle.” A nanoscience Ph.D. student can do this, and other nanoscience Ph.D. students can follow his example. Without exception, our interviewees were enthusiastic about this sort of project and thought it was a good way for nanoscientists to broaden their horizon (and, we would add, acquire further skills and competencies).

Over time, reflexivity-in-action will affect choices (and therefore the directions of research) regarding interactions and networking. As interviewee D put it: “You cannot have these conversations without being influenced by them.”

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## Appendix A: Interviewees

### Case 1: exotic molecule production

- A: Th. van de Sandt, Journalist. *Technisch Weekblad* (a weekly magazine for engineers).  
 B: A. Duyndam, Editor. *C2W* (a biweekly magazine for chemists).  
 C: B. Thijs, Senior Consultant. Synthon (a company that makes “exotic” chemicals and compounds with medical effects).  
 D: J. van de Elst, Senior Director. Philips Applied Technologies (an electronics and consumer products firm).  
 E: A. Rowan, Professor of Organic Chemistry, Radboud University, Nijmegen.

### Case 2: drug development

- A: Th. van de Sandt, Journalist. *Technisch Weekblad*.  
 B: A. Duyndam, Editor. *C2W*.  
 C: B. Thijs, Senior Consultant. Synthon.  
 F: B. Kokke, Researcher. Organon (a large pharmaceutical company).  
 G: P. Caspers, Senior Researcher. RIVM (a research institute in public health and environment with an expertise and advisory task to government departments).  
 H: R. van Weeghel, CEO. Zebra Bioscience (a company produces chemicals to study cells, genes and proteins for diagnostics and research).

## Appendix B: Interview protocol

All interviews were conducted at the work location of the interviewee, mostly undisturbed in a secluded room, and lasted about an hour. They were not recorded, but notes were taken during the interview, and these notes were worked out immediately afterward.

The interview began with a short introduction of the interviewer (DdB) himself, who then explained that he was working toward a Ph.D. in nanotechnology, but adding to it (a Ph.D.+ ) by studying potential applications of the techniques used in the lab, looking at locations where this technology might end up, and what this implies for the dynamics of innovation. A short explanation of the scanning tunnelling microscopy technique was given, and linked to the application that was the topic of the interview.

Then, a number of questions were put to the interviewee (with some variation, depending on how the interview proceeded):

- 1) It is probably still far in the future, but how realistic would you deem this technology?
- 2) From your point of view, what should be in place for this technology to actually work and be used?
- 3) What kind of technological advances are required?
- 4) From your own experiences, which actors might play an important part in attaining this? (For example universities or start-up companies).
- 5) With respect to the application environment, what kind of relationships and linkages should there be for this application to reach its potential?
- 6) What performance should this technique have to be a useful application?
- 7) What will be a critical factor for the success of the application?
- 8) Do people want this application at all?

Then, the interviewee was shown the detailed present “innovation chain network”.

- 9) What do you feel is missing in this network? Are there actors not present that should be?
- 10) Can you think of companies or persons that should be involved in this research?
- 11) After discussing this application of the STM in liquid technology, can you think of more applications using this technique?

At the end of the interview, the interviewee was thanked. It was mentioned that DdB might come back in three years’ time to ask additional questions so as to be able to write an update.

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