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Tracing emerging irreversibilities in emerging technologies: The case of nanotubes

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Abstract

This paper contributes to the development of methods for mapping and understanding the dynamics of emerging technologies. Our key concept is the notion of irreversibilities that emerge in the ongoing activities of researchers, institutes, policy makers and firms. Emerging irreversibilities denote the first socio-cognitive patterns that decrease the fluidity and openness, and that, eventually constrain and enable future activities. To trace the emerging irreversibilities we focus on the dynamics of expectations and the agenda building processes. A three-level framework is presented to analyse and visualise the dynamics in three interrelated contexts: the level of the research groups, the technological field and the society. This three-level framework allows the analyst to study different perspectives of a specific case and at the same time retain overview of the situation. By applying it to a particular application in nanotechnology, we will show that it is possible to trace the emerged irreversibilities. To conclude, we will discuss how the analysis of early dynamics is a vital ingredient of technology assessment studies that, indirectly (by means of the involved actors), seeks to influence the technological development at stake. By placing the constructive technology assessment (CTA) approach in a historical perspective of technology assessment, we will show the relevance of our method for CTA studies.

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Keywords: Emerging technology; Irreversibility; Technology assessment; Expectations; Agenda building

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1. Introduction

Assessing emerging technologies is a necessary, although difficult task. This originates from the fact that the early phases of technological development show a great deal of fluidity and open ends, while the routes that emerge may nevertheless lead to significant future rigidities (in terms of technologies, applications and stakeholders). If one does not just await the outcomes, the so-called dilemma of control applies. As Collingridge [1] emphasized, when a technology is in the early stages of development, it is very hard to foresee the social impacts of the technology, but the course of development can still be altered easily. When the technology becomes part of our economic and social system, social impacts can be observed. However, changing/controlling the technological development becomes extremely difficult. This dilemma highlights the importance of understanding the dynamics of technological developments even at very early stages. This implies that, when this understanding becomes sufficient, the course of development might be altered (controlled) when the technology is still emerging and not yet entrenched.

Emergence is the process or event of something coming into existence. For technological development this notion then relates to the very early stages of technological development. These situations inherently have to deal with high uncertainties [2], which means that options for the future are unclear, although slowly become clear. For example, there is a visible increase in the number of linkages between the heterogeneous actors together in search of defining the newly emerging field or technology. At a later stage technological trajectories [3] can appear, but in the emergence state no (or hardly) products are commercially available and no signs of, for example, a dominant design [4], are present. In this seemingly chaotic process it is important to look for the first signs that appear and indicate emergence. Furthermore, a systematic approach is necessary to map these indications that give insights in the situation. Here we will present a three-level framework that does just this.

In this paper we will address the issue how useful assessments can be made, given the enormous, but intrinsic uncertainties inherently related to emerging technologies. Our basic claim is that in order to appreciate and to influence developments in new emerging technologies, an understanding of the dynamics is necessary. As nanotechnology is the — partly intended, partly unintended — outcome of the moves of many actors in industry, research and policy, we need insight into the emerging patterns and mechanisms. We will discuss the phenomena and develop a method for tracing them empirically (Section 2); important here are the dynamics of expectations and the processes of agenda building. We will develop a three-level framework, which enables to trace the dynamics of expectations and agenda building in detail and we employ it in our case study. We will show that it is possible to trace emerging irreversibilities for a specific application of nanotubes (Section 3). We will conclude by placing our contribution in a historical perspective of technology assessment and by discussing the relevance of our method for constructive technology assessment, or CTA.[2]

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[2] Constructive technology assessment studies of nanotechnology are – at the moment – being performed in The Netherlands. These studies are part of a Dutch research and development programme that coordinates the efforts of leading research institutes and companies in The Netherlands in the area of nanotechnology. The preceding informal network was formed in 2001 and recently, in November 2003, it received a substantial funding of 95 Million Euro by the Dutch government, as well as its official name: NanoNed. An integral part of the NanoNed programme (3% of the budget) is the assessment of social, political, economical and environmental/health issues. Similar projects and funding can be seen in the other industrialised countries as well.

2. Method: tracing emerging irreversibilities

The basic claim is that a contribution to the understanding of the emergence of technological paths can be expected by understanding the role of emerging irreversibilities in technological development. Irreversibilities that emerge, enable and constrain actors in a sense that actors experience more or less resistance for different options they try to explore and develop. In time the emergence of irreversibilities results in some options becoming more dominant over others, and subsequently, a technological path could emerge. Emerging irreversibilities, therefore, are an indication and a driving force for the emergence of technological paths, i.e. some stabilisation is taking place. A definition of emerging irreversibilities can be as follows:

> *Emerging irreversibilities make it more difficult (or less easy) for actors to do something else (or easier to do something).*

As a rule in emerging technologies, the stakes and the expectations are high for various actors. At the same time, the situation is very fluid, unpredictable and no actor has clear knowledge what the technology will bring. Research institutes study a broad variety of scientific subjects and some results will be seen as promising and some not. The promising results and outlooks reshape the expectations for further research and eventually the research agendas [5]. Consequently, more institutes will start to work on the same subject, there is more attention in the journals, conferences on the subject are organised and so forth. That is, some paths are becoming less visible and probable, while others will gain more support and strength. As a result, there will be less fluidity in the emerging situation and actors will experience less available choices due to diminishing variety and decisions taken earlier [6]. These emerging irreversibilities reduce the complexity of the situation [7].

How do emerging irreversibilities affect the actors operating in the field? An irreversibility is something that cannot be undone easily, and when actors try to achieve something that go against the irreversibility, they become aware that it is impossible, or at least requires a lot of effort. Therefore, emerging irreversibilities are constraining. On the other hand, when actors try to achieve things in line with the irreversibility, the actor can rely on some predictability to improve the chances of his strategy, and this refers to the enabling character of emerging irreversibilities. The emerging irreversibility can be weak or strong, or, and this is something different, can be perceived as weak or strong. This perception of irreversibility ("we cannot achieve this due to...") could be proved false when an actor has the intention to test the irreversibility, i.e. tries actions or interactions that go against it. These actions can strengthen (confirm) or weaken the irreversibility depending on the outcome of the behaviour of the actor. In addition, irreversibilities often emerge behind the backs of the actors, i.e. without awareness of the actors.

For instance, the growing attention for a certain subject is an indicator for an emerging irreversibility. Fig. 1 shows the growing attention in journals for a certain topic and indicates that the term 'nanotubes' was increasingly used in the titles of scientific articles (extracted from the PiCarta database).

In 1999 a new specialised journal, the *Journal of Nanoparticle Research*, was established. This indicates the crystallisation of a new scientific community. The new outlet for publication on a new topic, and the early definition of a new audience indicate a next step in an emerging structure. While this step is reversible, in principle, it will be hard to undo in practice, because it

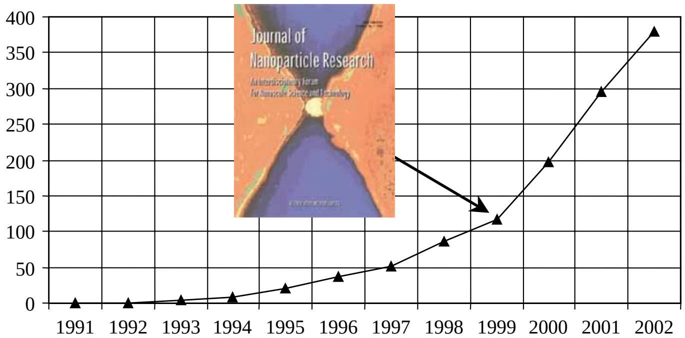

Fig. 1. Number of times 'nanotube' is mentioned in article titles (PiCarta).

has changed the perception and routines of researchers and has shaped expectations of a new audience.[3]

A second example of emerging irreversibilities are the *collective roadmaps*, which can be seen as articulated expectations about which path a collective of companies or an industry (as in the case of chip manufacturing) should follow for a certain period (say, 10 years). The fact that these roadmaps are made is an indication that actors involved in this process link up to reach a common goal. The path — as is written down in the roadmap — is the expression of the shared expectation that this is the right way to go. The roadmap, thus, functions as a device to keep the actors together. To deviate from it can only be done with increasing costs and effort, and this is exactly what indicates an emerging irreversibility.

The question, then, is how to trace emerging irreversibilities? We will focus on two ingredients of technological change that are especially important in the early stages: (i) the *expectations* that guide the search activities of scientists and firms, and (ii) the processes of *agenda building* [5,9]. Expectations have important roles in technological development. Since all involved actors — scientists, firms, policy makers — have to act under the condition of insufficient information, they will depend on the shared expectations that are present. Expectations shape the mindsets of the various actors, while, in their turn, expectations will be shaped and reshaped by research results, findings in other technical fields, or external forces. In general, expectations mould variation processes and guide selection [10]. Likewise, in processes of agenda building, variation is further reduced as certain topics are selected as important and urgent. Expectations are translated into the agendas of the different actors, upon which they act. The agendas give rise to activities and different outcomes (e.g., scientific results, a collaboration between companies), which will evoke new, often more specific, expectations and agenda building.[4]

We distinguish various interrelated levels where variation and selection occur: (i) locally, within a firm or research group, (ii) more general, within a technical–scientific field, and (iii) more global and diffuse, in society at large (see Fig. 3). The vertical dimension lists the three levels of aggregation. The first level deals with research groups. Here, research is done at very specific subjects. The second level refers to a

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[3] The fact that we use the emergence of this specialised journal for this paper is the fact that nanotubes is one of the major topics in this journal. What Roco [8, page 1] states as: "Research contributions on nanoparticles, clusters, *nanotubes*, nanocrystals, nanolayers, and macromolecules surrounded either by gases, liquids or solids, are brought together in this single publication."

[4] Earlier one of the authors has analysed this ongoing dynamic as the 'promise-requirement-cycle' [5]. Alternatively, one could focus on emerging networks of actors and artefacts: the preferred entrance point of actor network theory [6,11]. Then, the analyst would trace the emerging concentrations in actor-networks (e.g., firm cooperation, joint research efforts), as indicators of emerging irreversibilities.

	Basic research	Market
Society	How are the technological developments from the scientific viewpoint taken up by society?	How are the technological developments from the market viewpoint taken up by society?
Technological field	What are, from a scientific point of view, the different options and focus points?	What are, from a market point of view, the different options and focus points?
(Research) group	What are the results from (academic) research groups that contribute to the realization of the technology?	What are the results of private companies that contribute to the realization of the technology?

Fig. 2. Questions that are raised in order to address the dynamics of expectations and processes of agenda building.

technological field, with its dedicated journals, conferences and communities. The third level relates to the societal level, where governments, NGO's and other societal actors articulate the social, political and economic aspects of the new technological field. The horizontal dimension distinguishes between different core areas of technological activity: basic research and research for market applications. Note that the levels are dynamic and interrelated. In addition, each level will have its own timescales: changes at societal level have a slower pace than at the level of individual research groups [7]. Fig. 2 shows what questions should be raised in order to address the particular cell in the matrix and Fig. 3 gives typical sources to address the questions. By answering these questions empirically, main findings can be distilled. Subsequently, from these findings emerging irreversibilities can be derived. These steps make up the method we employ in this paper to perform the case study. These steps are elaborated on in Section 3.

The case we discuss in the next section deals with nonvolatile memories based on nanotubes. We chose this application of nanotubes in electronic devices, because it is — as will become apparent — a dynamic case among the (still) very few applications of nanotubes in electronic devices that also shows some commercial activity.

	Basic research	Market
Society	Reports by NGO's Reports by government agencies Spokesperson statements	Reports by NGO's Reports by government agencies Spokesperson statements
Technological field	Review articles that give an overview of the developments in the field	Reports that translate technological developments into market potentials Articles addressing the market potentials of technological developments
(Research) group	Articles in scientific journals	Press releases of individual firms Articles that address the developments and potentials of applications

Fig. 3. Possible sources to answer the questions raised in Fig. 2.

3. Case: nonvolatile memories based on nanotubes

Before explaining the details about nonvolatile memories based on nanotubes, we first briefly introduce the area of nanotechnology and nanotubes. Nanotechnology is a rising star in the set of new and emerging technologies. Many countries and firms feel the need to explore and stimulate its possibilities. The future of nanotechnology has become an important topic for technology firms, policy makers and research institutes. Typically, when new technologies emerge, they are accompanied by promises of all sorts. Earlier examples are biotechnology, genomics and microelectronics, or, more general, ICT. The media tell us, for example, that the new technology will definitely change our lives. It is a so-called 'generic technology' [12] since it can be used in all kinds of products and production processes, and thus, will have an impact in all areas of economic activities (examples are the materials production industry, pharmaceutical industry, electronics industry). Although nanotechnology is still in its exploration phase, industry, governments and research institutes already have high stakes in the future application. To illustrate, it is estimated that governments and large firms invested over $2 billion in nanotechnology worldwide in 2002 [13].

No single definition can be given for nanotechnology, as definitions abound [14]. We define it as the ability of controlled manipulation at the nanoscale (1–100 nm)[5] in order to create revolutionary new materials and systems that relate directly to the nanoscale. The ability to control matter at such small length scales got a big push by the development and improvement of a variety of microscopes (e.g., the atomic force microscope, AFM)[6] in the mid-eighties, which made the visualisation of the atomic region more and more accessible for scientists. One of the first landmarks is the Nobel Prize discovery of a new carbon molecule containing sixty carbon atoms (C_{60}) in the shape of a ball in 1985 (also called a bucky ball) [15]. Nanotechnology is seen as an enabling technology, which means that it enables different industries to improve their products, but will not likely (at least not at the short-term) make products on its own. That is, conventional technologies are still needed as well to produce the product. Nanotechnology can, for example, enable precise targeting of drugs (pharmaceuticals) or make computer screens flexible (electronic industry).

In this paper we focus on a special kind of nanosized particle, the carbon nanotubes, which has the same basic structure as the bucky ball. The term nanotube is generally used to refer to the carbon nanotube, which can be visualised as a sheet of chicken wire, which is rolled up into a cylinder where the loose wire ends seamlessly join (Fig. 4).[7] In the remainder of this paper we will use the term 'nanotube' instead of 'carbon nanotube'.

The promising developments of nanotubes, and nanotechnology in general, have led, at least according to some analysts, to a nanotechnology hype [13]. Various images about nanotechnology were brought into the world by media, spokespersons, etc., that sketch the seemingly unlimited possibilities that nanotechnology has to offer. Typical examples are very small robots that can conduct operations inside the human body or an elevator into space based on a nanotube cable. While these examples may be farfetched, they feed expectations by various actors in society (e.g., the public, politicians, firms). On the

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[5] 1 nm is approx. 1/80,000 of the thickness of a human hair or six hydrogen atoms in line.

[6] IBM researchers (G. Binnig and H. Rohrer) received the Nobel Prize for their discovery of the scanning tunneling microscope (STM). This microscope used an ultra fine tip to scan materials atom by atom and is therefore a powerful tool to investigate structures at the nanoscale. This discovery was the beginning of a whole range of microscopes achieving the same precision, but with different methods (e.g., AFM). These later developed microscopes are also capable of manipulating matter atom by atom.

[7] In production however, the nanotubes are formed directly.

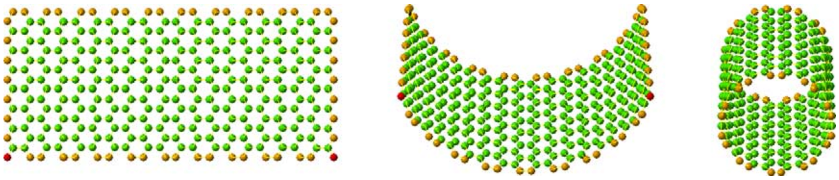

Fig. 4. A rolled up single sheet of carbon atoms (graphene) to visualise a single-walled carbon nanotube.

other hand there are growing concerns about the development of nanotechnology. NGOs and the media became aware of nanotechnology and addressed their concerns. Here again, we see topics that relate to the very far and speculative future such as nano-systems that control (and reproduce) themselves, but also immediate concerns that are based on today's science, such as toxicological effects of nanoparticles [13].

After this general introduction of nanotechnology and nanotubes, we now turn to the application that will be the subject for the remainder of the paper. A promising application of nanotubes is to use them as electromechanical[8] components in nonvolatile memories.[9] Nonvolatile means that the data remains intact when the power of the electronic device is turned off. For example, for personal computers, you can continue your work where you left it the previous day, like turning on the television, because the information is still present on the memory (this is called instant booting). In 2000, Rueckes et al. (Charles Lieber's group, Harvard University, Cambridge, Massachusetts) [16] published the architecture (Fig. 5) of how to make these nonvolatile memories based on the suspended SWNT crossbar (proof of principle).

In the "off" state (Fig. 6), the nanotubes have a certain distance between them. The lower nanotube is semiconducting, the upper nanotube is metallic.[10] The metallic nanotube will bend towards the perpendicular semiconducting nanotube when both are electrically charged (electromechanical process). The nanotubes will then stay in this position due to the Van der Waals forces.[11] These forces cause the nanotubes to remain their position, even when the power is turned off, giving the memory its nonvolatile character. The positions can be determined by measuring the resistance (directly related to the flow of electrons) between the nanotubes. In the "on" state the resistance is much lower, which allows determination between zero or one. By making a large array of these crossbars (every crossbar represents a bit), it is possible to make a memory chip.

The architecture explained above is the ideal solution. However, there are limitations in realizing this architecture (explained below), and therefore a hybrid solution has been developed and patented by

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[8] Electromechanical means that an electrical current can induce mechanical movement.

[9] Memory, which is commonly referred to as RAM (*Random Access Memory*), is a temporary (volatile) storage area utilized by the processing unit of every personal computer. Before a program can be used, the program is loaded from the hard drive into the memory, which allows the processing unit (processor) to directly access the program. The reason for this process is that hard drives are too slow to directly run programs from and therefore the program is temporarily (as long as you use it) loaded into fast memory.

[10] Different materials have a different resistance towards the conduction of electricity. Most metals (e.g., iron or copper) conduct electricity very well and are therefore used for wiring to transport electricity from one place to another. Insulating materials (e.g., most plastics) conduct electricity very poorly and are therefore used to shield wires from the environment. Semiconducting materials conduct less well than metals, but better than insulators. Transistors (the basic building block of computer chips) are made from semiconducting material. Nanotubes can have both properties, which depend on the geometry of the single-walled carbon nanotube [17].

[11] The Van der Waals forces are the physical forces of attraction and repulsion existing between molecules, which are responsible for the cohesion of molecular crystals and liquids. Van der Waals forces act only over relatively short distances and the forces are important in the mechanics of adhesion.

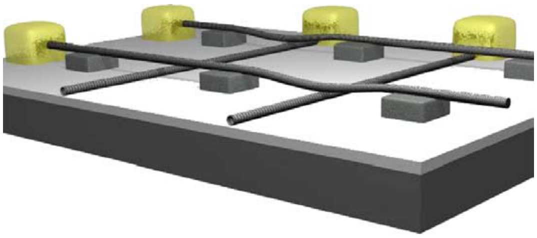

Fig. 5. Architecture of suspended nanotube memory [16].

Nantero (US Patent No. 20030165074). The intention is to commercialise this technology as soon as possible. In the hybrid solution the lower nanotube is replaced by a semiconducting structure created by common lithography techniques.[12] Then a layer of nanotubes is deposited and the unwanted nanotubes are etched away (again with common lithography).

G. Schmergel, T. Rueckes and B.M. Segal founded Nantero in 2000 (Rueckes being one of the inventors of the proof of principle). Nantero is developing NRAM™ — a high-density nonvolatile random access memory chip using nanotube technology. The company expects to deliver a product that will replace existing forms of memory, such as DRAM, SRAM and flash memory, with a high-density nonvolatile 'universal memory' [18]. This type of memory can be used in a wide variety of electronic devices (PCs, digital cameras, MP3 players, etc.). With this strategy they have been successful in getting several Venture Capital grants over the first few years of existence [19,20]. The company plays an important role in the development of nonvolatile memories based on nanotubes.

3.1. Tracing dynamics of expectations

The three levels in the framework can be specified in relation to the case. Therefore, we name the level of the research group: nanotubes used in nonvolatile memories, the level of the technological field; nanotubes in electronic devices, the level of the society; and nanotubes as part of nanotechnology. Such a case specific typology gives a focus for each level and is therefore useful to distinguish what the boundaries are of the case.

3.1.1. Society

The scientific developments, and understanding of nanotubes production and characteristics[13] have led to expectations on the level of the society. A spokesperson in favour of nanotube developments is Richard Smalley (Rice University, Houston, Texas). Considering the following statements from Smalley [21, page 1]: "Nanotubes will be cheap, environmentally friendly, and do wonders for humankind." With this statement Smalley stipulates (from a scientific point of view) a very bright picture for nanotubes.

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[12] Lithography is a common method used in the computer chip manufacturing industry to produce desired structures in materials.

[13] The research agenda on nanotubes have, in the last decade, changed considerably [21]. In the early 90's, especially the growth and (electrical, chemical and mechanical) properties were investigated in great detail. This research agenda shifted over the years towards the production capacity, controlled growth and applications of nanotubes. This also implicates that the variety of research topics has broadened. A broader spectrum is addressed, pharmaceuticals, new and enhanced materials, solar energy, etc. Also research is done from basic research (e.g., production capacity of single-walled carbon nanotubes) to applications and the production of the applications.

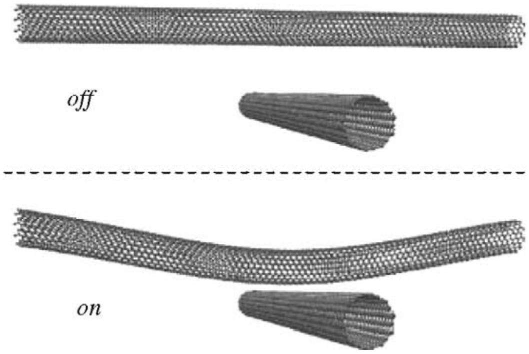

Fig. 6. "On" and "off" states of a suspended SWNT crossbar [16].

However, there are other voices that agitate against this. Arnall [13, page 7] for example states that: "Carbon nanotubes are already found in cars and some tennis rackets, but there is virtually no environmental or toxicological data on them." As well as the ETC group [22, page 72] who propose that: "governments should declare an immediate moratorium on commercial production of new nanomaterials (editorial: which includes nanotubes) and launch a transparent global process for evaluating the socio-economic, health and environmental implications of the technology." Arnall arrives at the same conclusion as the ETC group, which is applying the precautionary principle.

From the market side the expectations focus on the possibilities that nanotubes might have to improve or revolutionise existing products. Already nanotubes are used to strengthen materials (e.g., tyres or tennis rackets) and production facilities are set up to deliver the demand for nanotubes (MWNT and SWNT) that is expected for the coming years. Arnall [13, page 14] states here (taking a market perspective): "the most important material in nanotechnology today." Such statements give rise to the belief that nanotubes have much to offer in terms of applications. This is indeed the case when we look at how broad the application areas for nanotubes are generally addressed: pharmaceuticals, electronic devices, material production, energy technologies, etc.

Concluding, the expectations on the societal level show a contradiction in the sense that on the one hand nanotubes are used without regulation and on the other hand there is a public call (from various groups) that regulation is needed. However, the fact that nanotubes offer great promises for various industries is acknowledged.

3.1.2. Technological field

After the discovery of the single-walled nanotube in 1993, possible applications of nanotubes for electronic devices came out of the scientific community [21]. Using the straight tubes as wires in chips was one of the first options. In 1998, Cees Dekker's group [31] at the Delft University of Technology (Netherlands) turned a nanotube into a transistor (the basic building block of computer chips). This made it theoretically possible to build processors (the central computational unit of personal computers) out of nanotubes. However, the expectations are that commercialising this option still lies far ahead (at least 10 years).

Nanotubes can also be used to emit electrons. This opens up the possibility to use them as so-called field emitters to produce flat (even flexible) displays. The electrons emitted by the nanotube are pointed at a layer of phosphor, which as a consequence lights up. By making an array of pixels a screen can be obtained. In 1999, Jong-min Kim et al. at the Samsung Advanced Institute of Technology in Suwon

(Korea) did just that. The same technique can be used to produce vacuum-tube lamps in different colours that are twice as bright as conventional lightbulbs, longer lived and at least 10 times more energy efficient [23].

Since the publication of Rueckes et al. [16], where they introduce the architecture of nonvolatile memory based on nanotubes, it is clear that building these memories is one of the possible applications of nanotubes in electronic devices. We already discussed how this technology works, as it is the subject of this case.

Cientifica[14] [24] — from a market perspective — points out that, when the opportunities for nanotubes in electronic devices are discussed: "Big markets, apart from materials, in which nanotubes may make an impact, include flat panel displays (near-term commercialisation is promised here), lighting, fuel cells and electronics. This last is one of the most talked-about areas but one of the farthest from commercialisation, with one exception, this being the promise of huge computer memories (more than a thousand times greater in capacity than what you probably have in your machine now) that could, in theory, put a lot of the $40 billion magnetic disk industry out of business." It is clear that two applications are highlighted for expected short-term commercial use, flat panel displays and nonvolatile memories.

Important to mention from a market perspective (computer chip industry) is the following, as articulated by Collins and Avouris [23]: "Within this decade, the materials and processes on which the computer revolution has been built will begin to hit fundamental physical limits. Still, there are huge economic incentives to shrink devices further, because the speed, density and efficiency of microelectronic devices all rise rapidly as the minimum feature size decreases." These developments call for new techniques to continue the ongoing miniaturisation in the computer chip industry. Nanotechnology should give the answers here.

3.1.3. Research group

The expectations of using nanotubes for nonvolatile memories started with the Nature publication of Charles Lieber's group [16]. In this article they presented a proof of concept of the suspended SWNT crossbar and the architecture of the possible application. The authors address some problems in order to actually make the nonvolatile memories. Also, they state that: "The developments in these growth and assembly areas suggest that highly integrated SWNT device arrays, which represent the next step in our plans for molecular electronics, may be soon realized." What is meant by 'soon' however, is not specified.

In 2002, James Heath's group at the University of California (Los Angeles) reported that guiding the growth with an electric field could solve the problem of growing straight nanotubes [25]. This scientific result solved the problem of growing straight nanotubes.

Deposition of nanotubes into a parallel array (as is needed to create the hybrid solution) can be done in multiple ways. One can individually manipulate the nanotubes into the right position, however due to huge amount of nanotubes that needs positioning, this is no option. The second option is to use an electric field to grow the (straight) nanotubes onto the substrate [25] (as discussed above). A third way is to use a flow to guide the previous made straight nanotubes into position. Charles Lieber's group

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[14] Cientifica is the business information and consulting arm of CMP Cientifica, providing global nanotechnology business intelligence and consulting services to industry and investors worldwide.

reported the latter method in 2001 [26]. These scientific results solved the problem of deposition of the nanotubes onto a substrate.

The scientific results, as mentioned above, reinforced the expectations that nonvolatile memories could be produced. This can be shown by a statement of Ball [27] in an article where he discusses these results: "This proof of principle raises hopes that a nanotube lattice could form computer memory, storing one bit of information at each junction." He refers here to the original article [16], however these expectations are expressed 2 years later, after the new scientific results, which were obtained in the meantime.

At the market side, other dynamics are present. Here, Nantero — being the only company working on this technique — tries to mature the given technique (proof of principle) into a usable method for producing nonvolatile memories based on nanotubes. Nantero was founded in 2000 and they received the first Venture Capital grant in 2001 [19]. The fact that Nantero received this grant shows that the investors, based on their expectations, show confidence in a success of Nantero. In May 2003 a prototype of 10 Gb is ready and produced by standard semiconductor processes [28]. In September 2003 Nantero receives the second Venture Capital grant [20]. In the same month Nantero shows compatibility with lithography equipment from ASML [18]. In February 2004 Nantero [29] states they are on track for NRAM development.

Here we see that Nantero over the years has built on the expectations that nonvolatile memories will be commercialised soon. These expectations were formulated in the following way. In 2002 Rueckes et al. [16] state: "plans for molecular electronics, may be soon realized." In 2001 Nantero [19] states: "The company expects to deliver a product that will replace all existing forms of memory." In May 2003 Nantero [28] states: "Creating this enormous array of suspended nanotubes using standard semiconductor processes brings us much closer to our end goal of mass producing NRAM chips." In September 2003 Nantero [28] states: "Universal memory has been a dream for the semiconductor industry for decades — we fell that Nantero's innovative approach using carbon nanotubes and a nanoelectromechanical design can make that dream a reality in near term." In 2004 Nantero [29] states: "The proprietary manufacturing approach will enable for the first time the ultra-large scale integration (ULSI) of carbon nanotube-based devices in a deep sub-micron semiconductor fabrication line. In the near future, these innovations will allow NRAM™ to be one of the first mass manufactured nanotechnology products." Within these expectations we see a shift from discovery (2000), via a prototype (May 2003) to manufacturing a proprietary approach (2004). Hence, the developments at Nantero show a clear way towards commercialisation.

During these few years Nantero received a rather extensive media attention (37 articles in total) from technology as well as business journals. This is a clear sign that the media see Nantero as a promising company to take nanotechnology to the market. Also the fact that Nantero received the Venture Capital grants and especially the second round in 2003 is a sign that the investors expect Nantero to succeed, because venture capitalists perform extensive research before investing.

Concluding, different developments in basic research have given the building blocks that can be used to develop nonvolatile memories based on nanotubes. Nantero has taken up this challenge since 2000. Subsequent results in basic research as well as from Nantero have reinforced the expectations. These promising results have led to the second round VC financing for Nantero as well.

3.2. Tracing agenda building processes

3.2.1. Society

Are the expectations (concerns) about the toxicity of nanoparticles (incl. Nanotubes) taken up by policy makers and translated into programmes/regulation that reply to these concerns? Some initiatives have started over the last few years; we will mention the three most striking ones. First, the Royal Society and the Royal Academy of Engineering in the UK have incorporated these issues into their study (commissioned by the UK government, www.nanotec.org.uk) of nanoscience and nanotechnology. The goal is to carry out an independent study of likely developments and whether nanotechnology raises or is likely to raise new ethical, health and safety or social issues which are not covered by current regulation.

Second, at the level of the EU, a 6th framework programme has been approved. The NanoSafe project assesses the risks involved in the production, handling and use of nanoparticles in industrial processes and products, as well as in consumer products. The results are expected to indicate risks to workers and consumers, and to recommend regulatory measures and codes of practice.

Third, the ETC group is working to develop an International Convention for the Evaluation of New Technologies (ICENT), which it hopes to bring before a United Nations agency in 2004. This should create a new mechanism that will make it possible for the international community to monitor the development of new technologies whose introduction could affect (positively and/or negatively) human health, the environment, or society's well-being [30].

3.2.2. Technological field

None of the expected possible applications have come to a successful commercialisation yet. Therefore, basic research as well as efforts from the market side is focussed on realising the applications. The difference here is that basic research generally is conducted for all options and possible (not foreseen at this time) other applications, while the market side focuses (in general) on applications that are close to commercialisation. There are different topics that need (or needed) solving in order to be able to realise the expected applications. It is possible that a solution for a particular problem for one application can also be a solution for another application. An example is the problem that when nanotubes are grown, it is — until now — impossible to determine the electronic character (metallic or semiconductor) beforehand. Therefore, after growing, you end up with a mixture of metallic and semiconductor nanotubes. This is a problem, because often you need specific characteristics of the nanotubes in order to get a working application. To specify this example further, Cees Dekker's group at Delft University, showed in 1998 [31] that a single semiconductor nanotube could be turned into a transistor. In order to make, for example, a modern processor for personal computers, you need to have in the order of 100 million transistors. Without the ability to grow nanotubes with the right characteristics beforehand, a processor based on nanotube transistors is impossible to produce.

3.2.3. Research group

Restrictive factors in the development of technologies are repeating phenomena that end up on the agenda of research groups. Scientists observe hurdles for further development of a promising application (guided by the expectations) and start to work on solving the problems at hand. This process can also be observed in the development of nonvolatile memories. Typical problems addressed here were or are still the growth of straight nanotubes, precise deposition of the nanotubes on the substrate, and the separation of metallic and semiconductor nanotubes. Because not all problems were solved over the last years, Nantero adapted a (proprietary) hybrid solution that allows for some errors, and metallic and semiconductor nanotubes do not need to be separated. So, over the last few years some problems were solved and others were overcome by adapting the design. But, in the same period also the agenda changed from working on detailed technical problems (aiming at a prototype) towards scaling and production (making the technology ready for commercialisation). The last part was done in collaboration with ASML, which led to the fact that the technology is compatible with existing lithography equipment [18].

For the coming years Nantero not only aims at getting their product to the market, but also improving the existing technology to achieve even higher densities of suspended crossbars, which leads to larger memories. However, one of the problems cannot be influenced by Nantero, as stated in May 2003 [28]: "This process was used to make a 10 Gb array now, but could easily be used to make even larger arrays — the main variable now controlling the size is the resolution of the lithography equipment." At the same time, basic research groups work on fundamental insights in, for example, controlled growth of metallic or semiconductor arrays of nanotubes. Future scientific advances might improve the architecture of nonvolatile memories and eventually to the realisation of the ideal solution (Figs. 5 and 6). The same advances might also lead to more advanced architectures for other type of computer chips (e.g., processors).

3.3. Tracing emerging irreversibilities

Based on the evidence on the dynamics of expectations and agenda building processes as presented in the previous two paragraphs, we will now present main findings for each of the different cells in the matrix in Fig. 7. These findings also give answers to the questions as proposed in Fig. 2.

	Basic research	Market
Society	**Nanotubes as part of nanotechnology** Next to the acknowledgement that nanotubes offer huge possibilities, there is an open discussion on the possible toxic effects of nanoparticles (incl. nanotubes) on the environment and inside the human body. Some organizations ventilate their concerns on this topic and a few research programs have been initiated to address these issues.	**Nanotubes as part of nanotechnology** Apart from the concerns on the possible toxicity, industry started to produce nanoparticles with a strong growing increase in capacity. The market then focuses on the possibilities nanotube applications promise to improve or revolutionise existing products.
Technological field	**Nanotubes in electronic devices** The academic community addresses a wide variety of electronic devices based on nanotubes. These options are based on advances in the understanding of and the control to determine (beforehand) the characteristics of nanotubes. However, existing hurdles also restrain further developments. The timescales on which these applications might become viable differs a lot.	**Nanotubes in electronic devices** The market focuses on a selection of promising electronic applications based on nanotubes. The most promising are flat panel displays and nonvolatile memories. The fact that current semiconductor technology will reach the physical limits soon, gives a push on the market to come up with new solutions to continue the ongoing miniaturisation in the computer chip industry.
(Research) group	**Nanotubes used in nonvolatile memories** Step by step the problems around producing predetermined nanotubes and applying them for nonvolatile memories are solved (straight growth and deposition). Nevertheless, still some hurdles have to be taken to make the ideal solution (fig. 5) possible.	**Nanotubes used in nonvolatile memories** Nantero tries to mature the technique (proof of concept) into a usable method for producing nonvolatile memories based on nanotubes. Over the years two rounds of Venture Capital were received and successful collaboration with ASML was established. In the coming years Nantero aims at getting their product to the market and to improve the existing technology.

Fig. 7. Main findings located within the three-level framework.

These insights and empirical findings give the opportunity to trace emerging irreversibilities that arose around nanotubes and more specifically nanotubes in electronic devices, and nonvolatile memories based on nanotubes (Fig. 8).

We have shown that results of research groups directly give rise to expectations for promising applications and change the agendas for the future. Accumulation of research results (for instance, straight growth and precise deposition of nanotubes) solves the hurdles that before hindered promising applications to become reality. In the specific application we discussed in this paper this led (on the market side) to the realisation of a prototype of nonvolatile memories of Nantero. Later on, Nantero showed compatibility with existing lithography equipment as a next step in the realisation of a producible technology. We note that the opportunities that these scientific research results (straight growth, deposition), the prototype and the proof of compatibility brought to the field are emerging irreversibilities. These developments showed the academic and the business community that the technology (or even nanotechnology) is actually possible of producing workable products for the electronic industry.

The founding of Nantero, the allocation of two rounds of venture capital grants, and the collaboration with ASML indicate the emerging irreversibility that Nantero has become a central player in the realisation of highly integrated nonvolatile memories. This fact changed the market side in the sense that a robust player emerged within this industry.

The scientific community (related to the application of nanotubes in electronic devices) changed in the sense that since 1993 more and more attention was drawn to nanotubes. This led to the recognition of a specific set of promising applications (the same process happens at the market side, although a more limited set of options is recognised). The fact that such selections can be made indicates that a shared agenda exist about what is useful to work on. This leads to the emerging irreversibility that more groups work on subjects directly related to the realisation of these promising options.

At the level of the society we observed open discussions on different topics. This indicates a growing attention for various aspects related to nanotubes as part of nanotechnology. This at the societal level held discourse is marked as an emerging irreversibility.

	Basic research	Market
Society	**Nanotubes as part of nanotechnology** Societal discourse on nanotubes	**Nanotubes as part of nanotechnology** Societal discourse on nanotubes
Technological field	**Nanotubes in electronic devices** More research groups work on similar problems related to nanotube applications	**Nanotubes in electronic devices** Recognition of a specific set of promising applications
(Research) group	**Nanotubes used in nonvolatile memories** Possibilities where opened up by scientific research results that took away hurdles in using nanotubes for electronic devices	**Nanotubes used in nonvolatile memories** Nantero as a surviving central player in realising nanotube applications in nonvolatile memories

Fig. 8. Emerging irreversibilities located within the three-level framework.

As mentioned in Section 2, the levels in the three-level framework are interrelated. A few examples from the case where this is visible will now be highlighted. First, basic scientific results at the level of the research groups can influence the level of the technological field, because the results shape the expectations about the most promising applications. Second, sentiments at the societal level might influence the possibilities for the electronic industry to develop technologies that might receive negative publicity. This effect can also be reversed; extra incentives are present when a certain technology is received positively at the societal level.

4. Conclusions and discussion

In this paper we proposed a route to deal with the intrinsic uncertainties of a new emerging field like nanotechnology. The hopes, expectations and also the increasing social concerns raise questions about the possibilities to assess the ongoing developments. And while Collingridge's [1] dilemma of control definitively applies in this case, the concept of 'emerging irreversibilities' helps to locate the first signs of new socio-cognitive patterns that will constrain and enable future developments. The three-level framework makes it possible to gather findings of these first indications.

As nanotechnology is still in the early phases of development, co-construction by all possibly relevant actors is not straightforward. Therefore, we suggested in this paper that a focus on expectations and agenda building is helpful, as these are phenomena that can be observed early on in situations that show a great deal of fluidity and open ends. The three-level framework allows the analyst to study different perspectives of a specific case and at the same time retain overview of the situation. By applying the framework dynamically it was possible to identify emerging irreversibilities that directly relate to the case. It can therefore be concluded that by applying the method as developed in Section 2, insights in the fluidic situation and the dynamics of emerging technologies can be gained.

Our attempt relates to the historical trend of technology assessment methods to incorporate and exploit the actual technology dynamics [32]. A brief historical digression is helpful at this point. Technology assessment (TA) started in the late 1960s as an 'early warning' method [33], merely to inform parliaments about possible negative effects of new technologies. In the early 1970s[15] this more and more changed to a means for better policy analysis. During the 1980's, TA developed towards a policy instrument, where TA is used to support policy-making. Nevertheless, developments of TA were leading to different approaches in the United States compared to Europe. In the United States TA kept to policy analysis, while in Europe the approach is more focussed on addressing different social groups. In the late 1980s the notion of constructive technology assessment (CTA) became apparent in Europe. Many different types of CTA exist depending on the audience, phase of technological development, etc. Nevertheless, the leading idea is to anticipate on societal aspects in an early stage of technological development to get better societal embedded technology [34]. By striving to play an active role in the

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[15] The first dedicated technology assessment organisation was the Office of Technology Assessment (OTA) (founded in 1972). The OTA was closely related to the United States Congress, but ceased to exist in 1995.

development of 'useful' applications of technology, CTA indirectly aims at influencing the technology in development via the involved actors.

We think the tracing of emerging irreversibilities is an important next step in the development of TA, and especially in the light of constructive technology assessment. In general, CTA studies aim at assessing technological development in an active way in order to maximise the societal embedding of the new technology. Our basic claim is that in order to appreciate and to influence developments in new emerging technologies, an understanding of the early dynamics is necessary. As argued above, applying the proposed method helps to increase this understanding. The same method, thus, will be useful as input for CTA studies in which the perspectives and actions of multiple heterogeneous actors are involved. Understanding the dynamics from the different perspectives gives insight in the different points of view of the actors involved in the CTA study.[16]

Finally, we note that the emerging character of nanotechnology provides research opportunities for innovation and technology studies. The prevailing type of study in journals and books on technology dynamics is a retrospective analysis. The drawbacks of a retrospective approach are well-known: they tend to emphasize the dominant route that emerged as "winner" in the variation and selection process and, thus, to ignore the deeply fluid character of new emerging technologies in their first stages [11]. To study nanotechnology while it is unfolding at this very moment gives the opportunity to observe (for example with the method proposed in this paper) the construction of the technology in a more symmetrical way.

To conclude, the method proposed in this paper appeared useful to organise the data and to structure it into a credible story. By applying the method, insights are gained about the dynamics within the three levels and how the levels interact. These insights are valuable for understanding the dynamics of a particular technology and help to trace emerging irreversibilities in the early phases of technological development.

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References

[1] D. Collingridge, The Social Control of Technology, Pinter, London, 1980.
[2] R.R. Nelson, S.G. Winter, In search of useful theory of innovation, Research Policy 6 (1) (1977) 36–76.
[3] G. Dosi, Technological paradigms and technological trajectories, in: C. Freeman (Ed.), Long Waves in the World. Economy, Pinter, London, 1984, pp. 78–101.
[4] J.M. Utterback, Mastering the Dynamics of Innovation, Harvard Business School Press, Boston, 1994.

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[16] For example, one of the components of a CTA study (at least in some approaches) is the formulation of "socio-technical scenarios" [35], which supports the actors to formulate their views on the future. These views are directly related to the social perspectives on the new technology. As the set of involved actors is heterogeneous, the developed scenarios will differ in outlook and consequences. The proposed method will be useful to locate the various socio-technical scenarios and to view them in light of the dynamics at the separate levels. In addition, the results and insights that are gained by applying CTA tools in practice can be fed back into theories of technology dynamics.

[5] H. Van Lente, Forceful futures: from promise to requirement, in: N. Brown, B. Rappert, A. Webster (Eds.), Contested Futures: a Sociology of Prospective Techno-Science, Ashgate Publishing Company, London, 2000, pp. 43–64.

[6] M. Callon, Technological conception and adoption network: lesson for the CTA practitioner, in: A. Rip, T.J. Misa, J. Schot (Eds.), Managing Technology in Society, Pinter, London, 1995, pp. 307–330.

[7] A. Rip, R. Kemp, Technological change, in: S. Rayner, E.L. Malone (Eds.), Human Choice and Climate Change, vol. 2, Batelle Press, Columbus, 1998, pp. 327–399.

[8] M.C. Roco, Nanoparticles and nanotechnology research, Journal of Nanoparticle Research 1 (1999) 1–6.

[9] H. Van Lente, A. Rip, The rise of membrane technology. From rhetorics to social reality, Social Studies of Science 2 (1998) 221–254.

[10] H. Van Lente. Promising technology: the dynamics of expectations in technological development. Dissertation, Delft: Eburon, 1993.

[11] B. Latour, Science in Action, Open University Press, Milton Keynes, 1987.

[12] OECD, Technology and the economy: the key relationships, The Technology/Economy Programme, Paris, 1992.

[13] A.H. Arnall, Future Technologies, Today's Choices: Nanotechnology, Artificial Intelligence and Robotics; A Technical, Political and Institutional Map of Emerging Technologies, Greenpeace Environmental Trust, London, 2003, July.

[14] Royal Society, Royal Academy of Engineering, Nanoscience and nanotechnologies: opportunities and uncertainties, RS Policy Document, 2004.

[15] H.W. Kroto, J.R. Heath, S.C. O'Brien, R.F. Curl, R.E. Smalley, C60: Buckminsterfullerene, Nature 318 (1985) 162–163.

[16] T. Rueckes, K. Kim, E. Joselevich, G.Y. Tseng, C.-L. Cheung, C.M. Lieber, Carbon nanotube-based nonvolatile random access memory for molecular computing, Science 289 (2000) 94–97.

[17] T.W. Odom, J.-l. Huang, P. Kim, C.M. Lieber, Atomic structure and electronic properties of single-walled nanotubes, Nature 391 (1998) 62–64.

[18] Nantero, Nantero, Inc. announces collaboration with ASML compatibility of nanotube processes with ASML equipment proven. *Nantero Press Release* (September 2003).

[19] Nantero, Nantero, Inc. announces $6MM in funding aims to rapidly develop nanotube-based universal memory. *Nantero Press Release* (October 2001).

[20] Nantero, Nantero, Inc. announces $10.5MM in funding developing nanotube-based nonvolatile RAM technology for licensing. *Nantero Press Release* (September 2003).

[21] P. Ball, Roll up for the revolution, Nature 414 (2001) (November).

[22] ETC group, The big down, Atomtech: Technologies Converging at the Nano-scale, 2003 (January).

[23] P.G. Collins, P. Avouris, Nanotubes for electronics, Scientific American 283 (6) (2000 (December)) 62–69.

[24] Cientifica: The Nanotechnology Opportunity Report. 2nd edition (June 2003).

[25] M.R. Diehl, S.N. Yaliraki, R.A. Beckman, M. Barahona, J.R. Heath, Self-assembled, deterministic carbon nanotube wiring networks, Angewandte Chemie International Edition 41 (2) (2002) 353–356.

[26] Y. Huang, X. Duan, Q. Wei, C.M. Lieber, Directed assembly of one-dimensional nanostructures into functional networks, Science 291 (2001) 630–633.

[27] P. Ball, Cylinders make circuits spontaneously, Nature News Service (2002) (January).

[28] Nantero, Nantero, Inc. creates an array of ten billion nanotubes bits on single wafer standard semiconductor processes used. *Nantero Press Release* (May 2003).

[29] Nantero, Nantero's Dr. Thomas Rueckes garners awards and acknowledges company on track for NRAM development. *Nantero Press Release* (February 2004).

[30] ETC group, Playing god in the Galapagos, News Release (2004) (March), Issue 84.

[31] S.J. Tans, A.R.M. Verschueren, C. Dekker, Room-temperature transistor based on a single carbon nanotube, Nature 393 (1998) 49–52.

[32] A. Rip, T.J. Misa, T.J., J. Schot, Managing Technology in Society. The Approach of Constructive Technology Assessment, Pinter Publishers, London, 1995.

[33] R. Smits, A. Leyten, Technology assessment, Waakhond of speurhond? Translation: technology assessment: watchdog or tracker dog. Dissertation, Zeist, Kerckebosch, The Netherlands (1991).

[34] J.W. Schot, A. Rip, The past and future of constructive technology assessment, Technology Forecasting and Social Change 54 (1997) 251–268.

[35] F.W. Geels, Towards sociotechnical scenarios and reflexive anticipation: Using patterns and regularities in technology dynamics, in: K.H. Sørensen, R. Williams (Eds.), Shaping Technology, Guiding Policy: Concepts, Spaces and Tools, Edward Elgar Publishing, Cheltenham, 2002, pp. 359–385.

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