Technology Analysis & Strategic Management
Vol. 18, Nos. 3/4, 411–428, July–September 2006

Characterizing the Emergence of a Technological Field: Expectations, Agendas and Networks in Lab-on-a-chip Technologies

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ABSTRACT *In this paper we develop and use mapping tools to investigate emerging technological fields by studying the dynamics of expectations, agenda building and early networks. In our approach, expectations describe shared beliefs with regard to prospective entities and positions. Agendas are sets of priorities present to guide the actors in their work. The structure that arises as a result of the actions and interactions of actors is the emerging network. For emerging technologies these processes are susceptible to change and the technological paths that may arise are still easy to influence. We propose that not only looking at expectation dynamics, but also including agenda setting and networks dynamics is essential in order to successfully capture the complexities of the emergence of technological paths. A major challenge for this work lies in unveiling the socio-technical dynamics leading to path emergence. For this purpose we investigate the phenomena of irreversibilities that emerge during the ongoing interactions of researchers, institutes, policy makers and firms. With these aspects in mind, we will use a broadened view of expectation dynamics in order to arrive at an improved understanding of the building blocks of path emergence. We illustrate our approach with a case study of Lab-on-a-chip technology for medical and pharmaceutical applications.*

Introduction

Today, during their early stages, new science and technology fields generate considerable interest from scientists, businesses, policy makers, and the investment community. In understanding and managing for improved societal embedment of new technologies,[1] it is attractive to look at early stages in emergence, where the situation is more malleable and susceptible to change.[2] During this period of emergence, the situation is complex and seemingly chaotic, making it nigh impossible to steer and manage. To allow for the possibility of managing such complex situations, a deeper understanding of the dynamics

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0953-7325 Print/1465-3990 Online/06/3–40411–18
DOI: 10.1080/09537320600777184

that contribute to the emergence is called for. Further development of the conceptual understanding of emergence and methodological practices is needed. With this in mind, this paper makes attempts at both developing the understanding of emergence and methodological practices in order to elucidate important dynamics that contribute to emergence.

In line with the theme of this special issue of *Technology Analysis and Strategic Management*, we investigate the dynamics of expectations in an emerging technological field and important dynamics to which it is coupled. The studies of expectation dynamics have shown that, especially in the early stages of technology developments, expectations play a crucial part in defining roles, building interest and constructing mutually binding obligations.[3] The process of agenda setting is closely related to the dynamics of expectations, where shared priorities for work are articulated for realizing expectations.[4] Infant technology fields also create, and are shaped by, networks that emerge and carry (and are carried by) the field. These network interactions, combined with expectation dynamics and processes of agenda setting contribute to the emerging field, and possible path emergence, by shaping the ongoing activities and growth rate.

A deeper understanding of path emergence, and improvement of means to study early-stage technology fields would benefit from broadening expectations to include agenda setting and networking behaviour. Understanding and measuring the interplay of these three aspects and the consequences for the possible emerging path would enable more informed managing of emerging technologies. Therefore a question that will be addressed in this paper relates to identifying those phenomena that facilitate path emergence. We name such phenomena 'emerging irreversibilities'.[5] The aim is to gain an improved understanding of how to investigate emerging via assistance of a triad of expectations, agenda setting and emerging networks. In parallel we develop and use tools to visualize our data and to seek patterns therein. The approach is illustrated with the field of Lab-on-a-chip technology.

Lab-on-a-chip technology (miniaturized (bio)chemical analysis) shows roughly 15 years of scientific development, which gradually attracted other actors (e.g. businesses and end-users). The many possible chip components (e.g. for cleaning, separating and detecting), and the amount of previously separated fields provide examples aplenty and characteristics to explore and study a variety of manifestations of emerging irreversibilities. We will focus on describing in detail, two examples of emerging irreversibilities: (1) the way the introduction of polymer (as a material to produce chips) instead of glass/silicon enabled more actors to enter the field, and (2) broadening the membership of the field triggered and sustained by the development of microreactors.

The following section begins with an introduction to the concept of emerging irreversibilities and the research triad consisting of expectations, agendas and networks. The methodology and tools used in the case study are then developed and followed by the history of Lab-on-a-chip technology. The two examples of emerging irreversibility will then be explored. A discussion of insights gained from our investigation into the emerging field and recommended follow-on activities will round off this paper.

Theory: Building up the Triad

Within any emerging technological field, actors begin to link up with certain discourses and practices. The types of discourse differ widely at early stages, but over time, as a field emerges, alignment occurs around more or less shared discourses and practices. The crystallization of steering phenomena (out of the multi-actor dynamics) acts as anchor points, which guide and drive the field. The 'crystals' we refer to as emerging irreversibilities can be seen as punctuations in the evolution of a technological field. A broad functional definition on which to build via further conceptualization can be given as follows:

> Emerging irreversibilities facilitate specific technological paths (make it easier to act and interact) and constrain others (make it more difficult to do something else).

A key notion here is that emerging irreversibilities enable and constrain actors in the sense that actors encounter more or less resistance for the different options they try to explore and develop (this can be hidden behind the backs of the actors). When actors try to act against irreversibilities, this requires effort. The converse is true when actors try to achieve things in line with irreversibilities. Actors can then rely on some predictability and therefore improve the success of their strategies. The greater the degree of irreversibility, the more difficult it becomes for actors to go against it.

Over time, as irreversibilities begin to emerge and accumulate, some options become less visible and probable, while others gain more support and strength, and subsequently a technological path could emerge. This paper does not elaborate on the path of Lab-on-a-chip technology itself, but focuses on the growth in activity and significance of the field and irreversibilities that arise along with it.

The concept of emerging irreversibilities can gain some insights from studies of evolutionary economic studies of technical change and innovation.[6] The literature on path dependency discusses the power of technical interrelatedness,[7] increasing returns and lock-in. However, for studies of emerging technologies (and for managing for improving processes of emergence) this literature is disappointing due to its origins in focussing on sub-optimal routes being taken and lack of exploration of indicators. Path creation literature shows a break away from pure path dependency,[8] acknowledging agency in 'mindful deviation' and the mobilizing of resources by actors leading to the creation of new paths. However, to-date, very little work has been done on the processes that lead to path formation of early stage technologies. The investigations in this paper seek to add and deepen this emerging body of literature through developing and exploring the notion of emerging irreversibilities as indicators, or early signs, of dynamics of emerging technology fields.

The strength of the emerging irreversibility concept is to observe indications that influence the characteristics of various dynamics. Because the definition given above leaves room for a wide range of emerging irreversibilities, examples could include artefacts that have been demonstrated and accepted as part of the field, shared standards and goals, financial investments or the inclusion of new actors in the emerging field. Here, we take a close look at a material artefact and an instance of a new actor entering the field, as emerging irreversibilities, which shape the direction and amount of activity.

There are, of course, other emerging irreversibilities we could have focussed on, which are interesting for follow-up projects (see discussion). Focussing on a few types means we can deepen our insights into this concept of and the methodology to explore emerging irreversibilities. Such deeper conceptual and empirical explorations are lacking in the literature and it is towards this end, we concentrate our efforts.

The Dynamic Interplay of Expectations, Agenda-setting and Actor Arrangements

Figure 1 shows the triad of relations mentioned above. The characteristics of the activities in the field, related to each point of the triangle, revolve through the triad many times during the emergence of a field. As this happens, various emerging irreversibilities are produced from (crystallize out) the ongoing activities in the form of actor arrangements, relations, practices and routines. These emerging irreversibilities shape the ongoing activities related to the three points of the triad. The circulation of the triad and the accumulation of the emerging irreversibilities aid the characterization of the technological field through the early stages.

Here, we are concerned with expectations that become shared by different actors who influence the emergence of a technological field. In this process, a wider variety of actors become involved on the basis that (aspects of) expectations link up. This results in an increased visibility of the technological field as a whole. This often results in visions that become dominant in a field: a prospective structure is set and becomes forceful.[9]

Expectations guide the activities of the actors within a technological field, while, in turn, expectations will be shaped and reshaped by research results, findings in other technical fields, successful commercialization, and external trends and forces.[10] Over time, choices are made and priorities are set, which results in shared agendas. For new and emerging science and technology, these processes result in an enlargement of the attention in related journals, conferences on the subject are organized, start-ups are founded and companies start collaborations.

As these agendas become operationalized in the ongoing activities of the field, actors link up with each other in various forms of networks. These networks are composed of mutual dependencies that can be based on shared rules and routines, on the exchange of intermediaries and their translation,[11] or on the exchange of resources,[12] etc. The focus is on linkages between the actors that form a dynamic, but nascent, network. This in turn constrains and enables their activities.

Feedback and feed-forward effects spawn from the emerging networks onto the dynamics of expectations and agenda setting. They surface as positions and routines of actors that enable and constrain in various ways. These feedback and feed-forward mechanisms are illustrated as a triad in Figure 1.

Naturally, the above-mentioned dynamics call for a multi-level analysis, because the actors in and close to the technological field operate in different arenas (technical, economic, political, and societal). The collection of data to track expectations, agendas and

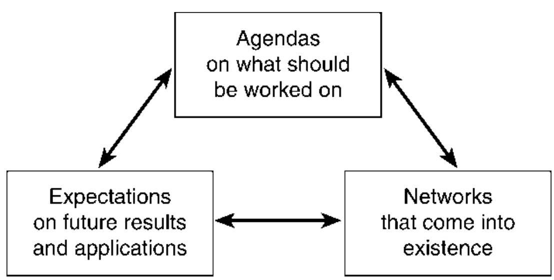

Figure 1. The research triad

networks then is also of a heterogeneous nature. In the next section, tools are developed to find patterns in data with these characteristics for a multi-level analysis.

Methods and Tools to Investigate Emerging Fields

With early-stage emerging fields conventional methods of measuring the degree of emergence, or amount of activity, can be misleading. For example, measurement of the occurrence and amount of relevant keywords in the literature regarding a technological field is recognized as being a useful indicator for a reasonably well-articulated field. However, when dealing with early-stage technological fields, keyword analysis can be deceptive because of the fact that keywords may be used in different ways, by groups of heterogeneous actors who give different meaning, owing for example to diverging expectations and evaluation routines. To allow for further characterizing the keyword analysis, the statement around the keyword must be analysed. We make the study of keywords context-sensitive by investigating and classifying statements made in texts, whether they deal with an expectation, an intention of agenda setting or actor relation. This results in a database with three types of statement connected to sources and dates. This then enables the tracking of the triadic behaviour in the field irreversibility over time. It also serves as the empirical basis of our work and the operationalization of the research triad. In short, we investigate emerging irreversibilities by looking at how the emerging irreversibility is articulated in expectation, agenda and network statements. The triad therefore becomes an investigation tool. This data set is triangulated with another data set obtained through semi-structured interviews with 20 experts from the field.

The heterogeneity of the actors involved provides yet another complication with regard to the heterogeneous data sources, which include information on collaborations between research groups and businesses, research results, venture capital interests and communications issued by interest groups. To tackle this problem, we have refined a tool for structuring the data, a 'three-level framework', which allows multi-level structuring of the data and presents the data in such a way that the possibility to observe patterns in the data is improved.

The Three-Level Framework

This tool has been used previously where they used a series of steps to apply the tool to structure heterogeneous data,[13] with a view to enabling the investigation emerging irreversibilities. Typical sources for the desk research are shown in Table 1. Here, we use its structuring and visualizing attributes to illustrate the case examples; in order to show indicators of which dynamics are going on and at which level.

The three-level framework distinguishes between two core streams of technological activity: publicly financed basic research and privately financed research (including the realization of market applications). These streams are divided into three distinct levels: (1) within research groups (public) or firms (private), (2) within a technical-scientific field, and (3) in society at large.

The first level describes the processes that are present within and between research groups and firms. Research is conducted on very specific and widely varying subjects. Also, research groups work together on certain topics that can be picked up by a large established company or start-up. The second level refers to a technological field, with

Table 1. A three-level framework filled-in with data sources

	Public	Private
Society	• Reports by NGOs and interest groups • Reports by government agencies • Spokesperson statements	• Reports by NGOs and interest groups • Reports by government agencies • Spokesperson statements
Technological field	• Review articles that give an overview of the developments in the field • Reports on research consortia	• Reports that translate technological developments into market potentials (for example for venture capitalists) • Articles addressing the market potentials of technological developments (for example from consultants)
(Research) group	• Articles in scientific journals	• Press releases of individual firms • Articles that address the developments and potentials of applications

its review articles,[14] conferences and communities at the public side. In the private stream, industry networks, venture capitalists and consultancy companies also fight for their share of participation on the first level. The third level relates to the societal level, where governments, interest groups and other societal actors articulate the social, political and economic aspects of the new technological field. Naturally, the different levels influence each other in various ways. In addition, each level will have its own timescales: changes at societal level have a slower pace than changes at the level of research groups.[15]

Charting Actor Demographics

This tool was developed to allow us to visualize the actors, visions and technologies that are present in the field of Lab-on-a-chip over time. We have named the charting of components of the network the 'actor demographics', placing the components on the diagram if they appeared in the database of statements.

Visions refer to expectations shared by multiple actors. We also place in the chart guiding technological artefacts in the form of prototypes and more developed technologies, which influence the emerging field. We will apply this tool on our database to show the changing actor demographics over time for the case of Lab-on-a-chip technology. For clarity, and to distinguish different types of actors, we have divided the chart into five areas (see Figure 2). The outermost four sections are arenas where public researchers, actors from the private sector, the government and legislative bodies, or the (possible) users of the technologies can be found. This demarcation of actor groups comes from the rich case history, and is a means of supporting the case history in a clear way. The central box houses the visions that circulate in the field and the technological artefacts that play a role in the field. The tool does not give an indication of the linkage between actors, artefacts and visions, but merely maps the membership of the emerging field. Other charts are possible, for example by including linkages or placing the elements of the central box next to the actors where they appear, but we will explore this in a

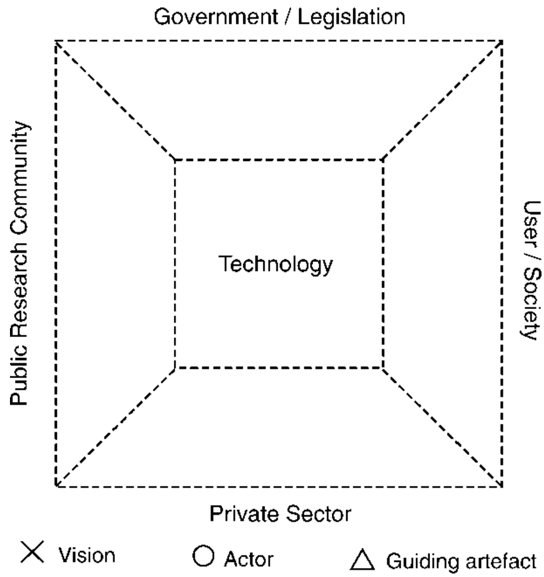

Figure 2. Empty actor demographics map

follow-on paper.[16] We have not investigated in detail the role and 'shaping strength' of the guiding technologies and visions. The simple actor demographics tool was sufficient to support the construction of the history and to reveal basic patterns.

Case: An Analysis of Lab-on-a-chip Technology

This section first outlines the history of Lab-on-a-chip technology supported by mapping the actor demographics. Then, two emerging irreversibilities are explained in greater detail. The three-level framework is used as an aid to explore the examples. We focus on medical and pharmaceutical applications alone.

History of Lab-on-a-chip Technology

Lab-on-a-chip technology had its roots in microtechnology fabrication technologies, which enabled the fabrication of the first fluidic chips at the end of the 1980s. These early laboratory experiments inspired the scientists to lay down high goals for the field, which are still alive and circulating today:[17] Lab-on-a-chip technology should create complex systems that integrate all necessary analysis steps on one chip, labelled as a Micro Total Analysis System (μTAS). The agenda was set to miniaturize existing laboratory analysis instrumentation and therefore, in the main, analytical chemists where attracted to the development of these microfluidic systems. Figure 3 shows the actor demographics in periods of 5 years.

In the early 1990s high expectations were raised about the possibilities of performing (bio)chemical analysis at any location and at anytime,[18] for example, total blood analysis at the patient's bedside (point-of-care testing). In 1993, Harrison and Manz revealed a large breakthrough in the journal *Science* with a successful miniaturization of the

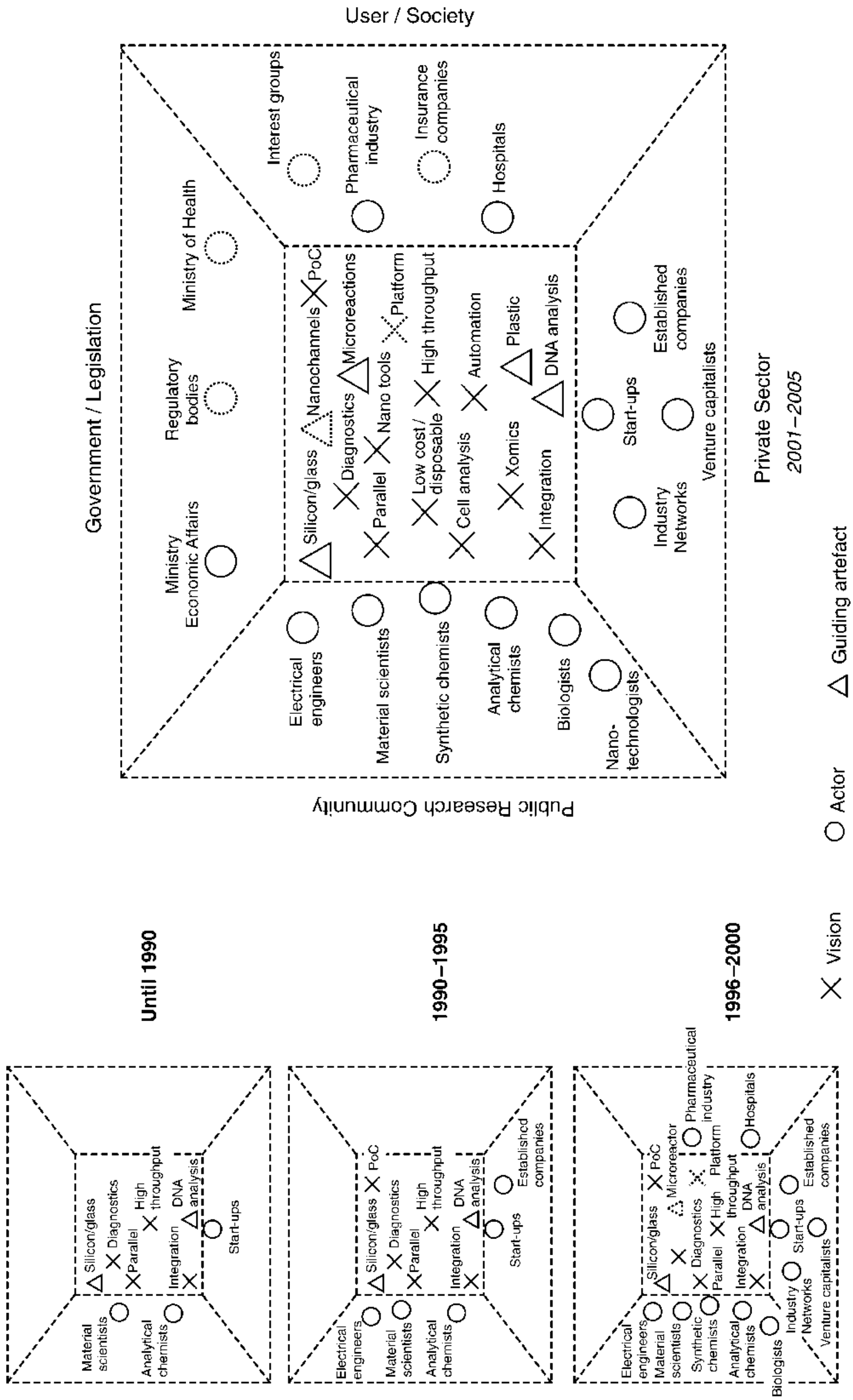

Figure 3. Actor demographics for Lab-on-a-chip technology

analytical technique capillary electrophoresis.[19] They articulated their expectations as follows (p. 897): 'The application of micromachining techniques to the miniaturization of chemical analysis is very promising and should lead to the development of analytical laboratories on a chip.' Typical advantages of chip-based analysis systems are speed, less sample needed and possibly portable.

In the mid 1990s other scientific communities, such as synthetic chemists and biologists, were attracted to the field. They foresaw that this emerging technology could aid them in their work or enable new lines of research. As a reflection of these developments the term Lab-on-a-chip (which was a broader notion than μ TAS) became used more widely. Synthetic chemists were interested because of the initial developments in microscale reactors on chip,[20] which resulted in a publication in the July 199 edition of *Science* by Whitesides *et al*.[21] For the biologists, the possibility to analyse and experiment with living cells (cellomics) on (often polymer) chips, was the main characteristic. Over the last 5 years, nanotechnology is entering this field. It offers improvements to existing chip components, but also provides novel concepts, for example, for separation and detection.

In 2002, Quake *et al*. reported the possibility to produce large-scale integration of microfluidic chips, which is in analogy with electronic integrated circuits.[22] This then reinforces some expectations, as Quake formulates it himself (p. 584): 'The rapid, simple fabrication procedure combined with the powerful valve multiplexing can be used to design chips for many applications, ranging from high throughput screening applications to the design of new liquid display technology. . . . the ultimate complexity and application are limited only by one's imagination.' This development is of special interest to pharmaceutical companies.

The present situation can be characterized by the first successful applications, e.g. laboratory electrophoresis chips, portable blood analysis systems, and platform for production) together with an intense search on where the state-of-the-art technology can be made feasible and stimulate more economic activity.

In conclusion, what we have seen is a technological field becoming more established.[23] What is noteworthy is that the field has grown in terms of members (active or passive recruitment) and hardly any actors have retreated from the field (see Figure 3). This effect highlights the emerging character.

An Example of Material Irreversibility: Polymer Chips

This example will elaborate on how a 'material irreversibility' is capable of generating significantly more effort that is being put into a technological field. The reason for this effect is that it enables other actors to become involved in various ways, because of specific characteristics of the material irreversibility (in this case ease of use and low costs). At the same time, because of the functional limitations, it also allows other actors to stay on their track. Then the dynamics go further, because other actors start to work on the limitations and hybrids occur also. It will also become clear how the material irreversibility constrains actors that want to do something else. First a short history of using polymer for microfluidics devices is given.

Until 1996 glass and silicon were used to produce fluid chips. For making structures in glass or silicon one needs to use specialized facilities, such as a cleanroom.[24] Using a cleanroom is expensive and not widely available. This constraining effect is expressed as follows: 'The need for specialized facilities for fabrication prohibits the widespread use of this technology by researchers'.[25] Using polymer often revolves around this constraint. Polymer could be used before,[26] but new techniques made it possible to use smaller feature sizes with polymer,[27] with roughly the same resolution as with glass/silicon.[28] Also, Becker and Gärtner (p. 25) state: '... more and more academic groups are realizing the great potential for simple and fast in-house production of design prototypes with polymer fabrication methods'.[29] Also, the possibility of low cost production of disposable chips is often mentioned. Kan *et al.* (p. 3570) phrased the expectation as follows: 'The use of polymer and elastomeric microfluidic devices promises lower manufacturing costs, and could allow the creation of disposable and adaptable genotyping devices'.[30] Lee *et al.* [31] (p. 6544) also address this issue: 'The cost of fabrication in PDMS is low compared to that for many materials (e.g. glass or silicon) commonly used in microdevices ...'.[32] The effect was that from 1996 onwards, more research groups started to use polymer for producing their chips. An expression of agenda from Becker and Gärtner (p. 20) links up with this: 'A process that has found widespread use mainly in the academic world is the casting of silicone-base elastomers [eds. a type of polymer]'.[33] Becker and Gärtner (p. 25) describe the agenda as follows: 'The driving force behind this development, on the one hand, is certainly the commercialization of microfluidics with its applications in genomics, drug discovery, and diagnostics. These areas all demand a high number of devices at low cost. Ultimately the devices will be used in disposables.'[34] The increasing use of polymer can be shown by looking at the number of publications (Figure 4) where the word 'polymer' is used in the title and abstract of the MicroTAS conference proceedings from 1996 until 2004 (the largest conference in the field of Lab-on-a-chip technology).[35] After the introduction of the use of plastic in 1996 a growth is visible. Later (after 2001), the data are less conclusive, but plastic stays its ground.

There is a difference in use of polymer among the various disciplines involved in Lab-on-a-chip development. Biologists and chemical analysts often use polymer, while

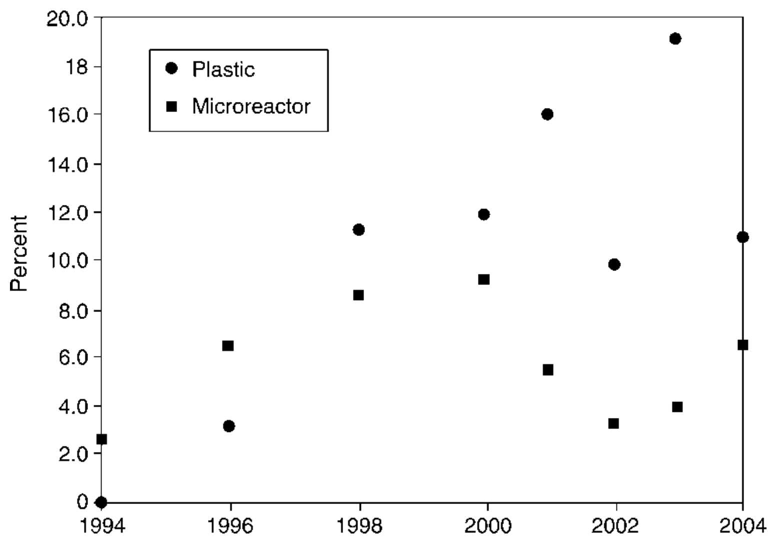

Figure 4. Papers addressing the use of polymer and microreactors (see example No. 2) as a percentage of the total amount of paper in the MicroTAS proceedings from 1996 until 2004

synthetic chemists hardly use it. The reasons for these differences can be found in the material properties. Synthetic chemists perform reactions on chips, and there is not much known about how polymers influence the reaction; although, a general exception are organic reactions.[36] Biologists are used to working with polymer and an additional advantage is that polymers are permeable to gasses and therefore it is easier to keep biological samples (cells) alive on chip.

Nevertheless, polymers still have their disadvantages. As a response to this, research groups now work on finding other polymers that suffer less from the drawbacks, but keep or improve the advantages. For example, at the Technical University of Denmark, a new research group (led by Geschke) have worked since 2001, on using lasers for rapid production of polymer microfluidic systems.[37] Other solutions are being sought in coating or treating the channel surfaces.[38]

Companies have also stepped into the field, using polymer to develop their products, building up the network even further. In 2003, Consultancy company Yole Development reported a series of those companies that generally use the argument of low cost production,[39] high-throughput screening and disposable chip. Examples are Gyros AB (founded in 2000) and Microchip Biotechnologies, Inc. (founded in 2003). Gyros develops and produces micro analysis systems based on a proprietary technology platform.[40] Professor R. A. Mathies is co-founder of Microchip Biotechnologies, Inc., which commercializes part of the technology developed at the University of California.[41]

Above, we saw expectation, agendas and network ties evolving through time around the use of polymers for fluidic chips. The strong effect on the field is visible by the sustained circulation in the triad over time, making the use of polymer a real emerging irreversibility for the field of Lab-on-a-chip technology. We can now show the dynamics of this emerging irreversibility in a three-level framework (Table 2). Using polymer for microfluidic chips enables other actors to join the field of Lab-on-a-chip technology, i.e. giving the field a push by enabling others to step in. We saw, for example, that low costs with less demand on specialized facilities caused this effect. Review articles also described the state of development for using polymer. However, polymer also constrains, because, for example, the limited feature size or chemical influences on reactions causes particular actors to continue to use glass or silicon. In addition, we saw that new agendas were set

Table 2. Three-level framework visualizing the developments on polymer chips

	Public	Private
Society	• No developments related to plastics	• No developments related to plastics
Technological field	• ±2000: multiple review articles are published on using plastics for microfluidics	• 2003: recognition of the possibilities by consulting companies
(Research) group	• Strong growth in research groups using plastics for chip fabrication from 1996 onwards • ±2000: research groups start to commit themselves to improve characteristics of plastics and production of plastic chips	• Frequent use of plastic for chip manufacturing in companies

and new research groups were built to come up with solutions to the drawbacks of using polymer. New businesses were founded using polymer for their developments, some of which were spun off from universities, so keeping the relationships with academic progress and illustrating mutual dependencies that lead to network formation. These activities also caught the attention of consultancy firms who linked them up with their agendas.

An Emerging Irreversibility Arising Through New Members Becoming Part of the Field: The Example of Microreactors

Microreactor technology has been selected to illustrate a form of emerging irreversibility,[42] which comes about when a new group of actors become a member of an emerging field and influences both the character and direction of an emerging field by becoming integrated in the growing network. We will explore the history of microreactor technology a little and the passive and active recruitment of microreactor technologists into the field of Lab-on-a-chip.[43]

Microreactors, generally defined as reactors that have microstructures for chemical reactions,[44] began to emerge around 1997.[45] In the review paper by Haswell,[46] a reactor design for flow injection analysis was described. There was a trend towards miniaturization in the field of synthetic chemistry, enabled by ever improving microfabrication techniques: 'many such problems [related to macro total analysis systems] may be overcome through system miniaturisation'.[47] During the very early stages of microreactor development the merging of the field of microreactors with that of Lab-on-a-chip became attractive, for example, Jensen (p. 293) wrote in his review of microreactor technology: 'The merging of μTAS techniques with micro-reaction technology promises to yield a wide range of novel devices for high throughput screening, reaction kinetic and mechanism studies, and on-line monitoring of productions systems'.[48]

The promise of highly efficient screening of functional materials, biologically active compounds, handling of highly explosive chemical reactions, or control of highly toxic chemical reactions, has meant considerable research interest. Microreactors promise many practical advantages over traditional batch (macro-scale) reactors, including safety, easy modulation, and parallelization possibilities for scaling-out towards industrial production.[49] In addition, many multi-phase reactions (sequence of reaction steps) could be carried out effectively in microreactors, which would otherwise be problematic or impossible in a batch method.[50]

Over the last 15 years, there has been considerable research on micro-scale structured devices for applications to chemical synthesis (microreactors). A large amount of academic research, as well as eight IMRET events (International Conference on Microreaction Technology), has created a substantial scientific activity in the field of fabrication individual microreactor units.[51] In addition to the growth of the microreactor field in general, the microreactor community (synthetic chemists) is now an accepted and working member of the Lab-on-a-chip field. This can be seen in the presence of synthetic chemists and microreactors in the MicroTAS Conference (see Figure 4). The data shows that the microreactor community, despite some variations over the years, established itself in the field. This was also backed during an interview with Sabeth Verpoorte (University of Groningen, the Netherlands) (24 June 2005) where she mentioned that the Steering Committee of the MicroTAS Conference encouraged the membership of research groups working on microreactors by inviting two key researchers in this field to participate in the Steering Committee in 2000–2001. This active construction of ties between formerly quite separate communities has repercussions for the field of Lab-on-a-chip. The microreactor community is now tied in with developments of Lab-on-a-chip, and thus expectations of the future of Lab-on-a-chip (including synthesis on chip as well as analysis) are tied to the field of microreactors.

In addition to the traditional microreactor community (the synthetic chemists) entering the field, some companies have also stepped into the development of microreactors, with varying degrees of success. In the pharmaceutical industry, there have been a few cases of processes employing small-scale structured devices for process intensifications on the production scale; most notably by Siemens Axiva, Merck, Clariant and Degussa.[52] Also, start-up companies have been working on microreactors. An example is Micro Chemical Systems Ltd. Founded in 2001 by Stephen Haswell, it has created a number of technologies including, in collaboration with GlaxoSmithKline, a microfluidic reactor.[53]

However, in contrast to the world of Lab-on-a-chip, research and development of microreactors is accelerating in the field of large-scale industrial chemical processing, which can be illustrated by a new European consortium with the acronym IMPULSE (Integrated Multiscale Process Units with Locally Structured Elements), which aims at the integration of process equipment (such as microreactors, heat exchangers and thin films) to obtain improved performance for the whole chemical synthesis process.[54]

Groups working on microreactors are embedded in two networks, namely large-scale industrial chemical processing and Lab-on-a-chip. The microreactor community thus acts as a node between these two fields. With the growing importance of microreactors in both fields, they are becoming increasingly bound together and the success of microreactors in either field will influence the other.

Table 3. Three-level framework visualizing the developments of microreactors

	Public	Private
Society	• No developments related to microreactors	• No developments related to microreactors
Technological field	• 2005: multiple review articles are published on microreactors (Of note: Microreactor double issue in the journal *Chemical Engineering Technology*) • Microreactors appear in MicroTAS proceedings • 1998 1st IMRET meeting	• 2005 recognition of microreactors as important both for Lab-on-a-chip and large scale fine chemical industry
(Research) group	• 2005 growth in research groups investigating microreactors (Of note: European network 'IMPULSE') • 1997 First on-chip microreactor demonstrated by Hull University (Haswell, Ref. 20)	• 2000–present: Large companies like Glaxo Smith Kline and start ups like MCS researching specific reaction focused microreaction technology • 2000/2001: Some commercially available microreactors begin to emerge for specific reactions (IMM Mainz, MCS Hull)

We can now construct the three-level framework (see Table 3), where we see how the emerging field of Lab-on-a-chip has been shaped by the recruitment of synthetic chemists. The fact that microreactors could be included in the chip system has brought new actors into the field as well as visions both carried with the synthetic chemists and new hybrids that are stimulated by the possibilities of microreactors and acceptance of their presence in the field.

Discussion and Conclusions

The aim of this paper was to investigate the phenomena that guide an early-stage technological field in certain directions rather than others. We have shown that broadening the study of expectations by including agenda building and network dynamics forms an approach that, when operationalized through analysis of statements, allows us to explore and deepen our knowledge of emerging irreversibilities as illustrated in the examples. Another objective of the paper was to develop and test a number of tools, to tackle the challenge of characterizing a technological field during its early stages of development. Our methodology of tracking expectations, agenda setting and emerging networks through statements in texts allowed the possibility of digging deeper into the dynamics of two emerging irreversibilities. A three-level framework allowed multilevel visualization and analysis of the heterogeneous data.

With the polymer example, we saw that new possibilities can stimulate more actors to participate in a technological field, which strengthens the field. Nevertheless, in the case of polymer, it appeared that following this route has limitations too, and those that use this technology are both enabled by the ease of using this material, but constrained by its limited applications.

The integration of synthetic chemists into the field is an emerging irreversibility because it has shaped the expectations of what Lab-on-a-chip should be: synthesis and analysis on a chip (rather than analysis alone). Thus further developments of the field of Lab-on-a-chip are based on this search heuristic. The shaping power of microreactors has grown as it has become more deeply embedded in the world of Lab-on-a-chip, but also it carries with it other ties, of particular note is the membership of microreactors in large-scale fine chemical synthesis. Because relatively high investments are being made into microreactors in this industry, progress in fine chemical synthesis could have a shaping effect on the Lab-on-a-chip field.[55]

The triadic view used has allowed us to understand, in greater detail than by studying expectations alone, the characteristics of a growing field, from expectations to agendas to manifestations that bind and shape multi-actor networks. Some manifestations take the form of visions and technologies, which are recognized and link up actors (for example Point-of-care, diagnostics, plastic and low cost/disposable are linked). These technologies and visions are forceful and guide the dynamics of networks as well as shape further expectations and agendas of actors. Thus, there is feedback and feed-forward between elements of the triad. Stating that forceful technologies and visions are possible emerging irreversibilities is justified and deserves further investigation. This challenge will be taken up in a follow-on paper, which will focus more on the relationship between actors, technologies and visions in the emerging field of Lab-on-a-chip technology and on the question of how to map these dynamics in more detail using linkages that are made in statements. This will require a more elaborated version of the actor demographics map including the strength and origin of the ties.

An interesting finding from the case history and indicated with the actor demographics is the fact that the field of Lab-on-a-chip technology only shows a growing trend. Innovation literature teaches us that in later stages of technology development, shake out of technologies and involved actors, occurs.[56] In this case, it means that 'no shake out' indicates the emerging state of field. Even though there is hardly any evidence of commercial exploitation of the developed technology to date, the ongoing growth of the Lab-on-a-chip field shows resilience to make the promises come true and to sustain the visions. The state of the field is still merely scientific, but has also attracted quite some business interest. At the same time, commercialization, standardization and actual use are hard to find. Will near future developments push the technological field into the next phase where competition and user selection will restructure the field? To set the field to a more self-propelling state (path emergence), emerging irreversibilities are needed at the business and user side. An example is standardization and the rise of a technology platform on which actors can build. This makes the applications more transparent to the users and leaves room for quick growth of applications. Another example is a (or a number of) 'champion' application(s) that enhances the visibility and use, extensively. Other actors can then build on this success and on increased acceptance of users.

Insights in emerging irreversibilities provide innovation researchers with an heuristic tool to learn more about how emerging fields develop and to reconstruct their short histories. Also, other parties from inside the emerging technological fields can use the insights to study the history and look towards the future in a more informed way. Supported by this information one can start to work on prospective exercises and foresight work. Assessment of possible technological paths is then a productive way to go. When integrated in exercises such as Constructive Technology Assessment,[57] this has consequences for involvement and managing emerging technologies.

In such activities one can still opt for working on prospective issues together with or without the actors in the field. Combining constructive technology assessment exercises with analysis of emerging irreversibilities and exploring possible futures with relevant actors is important. Not only for the quality and plausibility of the future scenarios, but also for the dissemination and use of the exercise in the ongoing decision-making processes in the emerging technological field. This paper has shown some important dynamics that shape technological emergence, laying the groundwork for further investigation and elaboration both in the typification of emerging irreversibilities and the role they play in emergence, as well as exploration of how they can be used in technology management.

Acknowledgements

The authors of this paper would like to thank Arie Rip, Ruud Smits, Harro van Lente, Sabeth Verpoorte, Kornelia Konrad, Stephen Haswell and Vincent Linder for their valuable contributions to this paper. Also, this work would not have been possible without the insights we received from our interviewees.

Notes and References

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14. Review articles are placed at the level of the technological field, because they give an overview and describe trends at the level of the field, in contrast to 'standards' scientific articles, which describe the results of one or a few research groups that do not represent the field as a whole.
15. Rip & Kemp, *op. cit.*, Ref. 5.
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