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Abstract. *Current changes in the science system, conceptualized as cyberscience, Mode 2 knowledge production or Triple Helix, have been debated heavily these last decades. This paper rearticulates these debates by studying the ways in which the emergence and use of ICTs have conditioned changes in the science system. We analyse these changes, based on empirical studies and theoretical conceptualizations, as an interaction at three levels: researching, scientizing and politicking. The analysis suggests that the main result of the use of ICTs in sciences is an additional layer of communication, providing heterogeneity on top of established patterns and allowing a recombination of new and established elements. Concepts of radical discontinuity in sciences are rejected and policy implications are offered on the basis of the analysis.*

Key words. *Cyberscience – E-Science – ICTs – Internet – Mode 2 – Science – Triple helix*

Résumé. *Les transformations actuelles du système scientifique, qui ont été conceptualisées comme cyberscience, 'Mode 2' de production de connaissances, ou Triple Hélice, ont été largement débattues au cours des dernières décennies. Cet article réarticule ces débats en étudiant comment le développement et l'utilisation des TICs ont conditionné ces changements. Nous analysons ces changements, à partir d'études empiriques et de conceptualisations théoriques, en tant qu'interactions à trois niveaux: à l'échelle du 'researching', à celle du 'scientizing', et du 'politicking'. L'analyse suggère que le principal résultat de l'utilisation des TICs consiste en l'adjonction d'un niveau supplémentaire de communication, qui ajoute un élément d'hétérogénéité aux situations établies et qui rend possible une recombinaison des éléments existants et de nouveaux éléments. Le concept de discontinuité radicale des sciences est écarté et l'article présente les implications politiques résultant de cette analyse.*

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Mots-clés. *E-Science – Internet – Mode 2 – Science – TICs – Triple Hélice*

Two strands of theoretical discussion underpin the current article.[1] The first relates to a set of concepts and ideas about changes in the knowledge-production system of the last decades. According to a growing number of scholars, the organization of scientific knowledge production and its role in society are going through a transition. In this context scientific knowledge production is said to become increasingly interrelated with social and economic objectives, and to take place outside the institutional regime provided by the university system and public research organizations. The growth of knowledge production in new areas and locations has been encouraged by the increasing tendency of states and other organizations to rely on formal knowledge for dealing with complex problems. In general the role of knowledge and scientific knowledge production vis-a-vis other social actors has been reorganized. Moreover the pre-eminence of theoretical and codified knowledge in modern societies is discussed in terms of the rise of an information, or knowledge-based, society (Webster, 2006). A number of heterogeneous concepts and ideas highlight different elements of this reorganization: 'national systems of innovation' (Lundvall, 1988), 'research systems in transition' (Cozzens et al., 1990), 'the post-modern research system' (Rip & Van der Meulen, 1996), the 'Mode 2 of knowledge production' (Gibbons et al., 1994), 'Triple Helix' (Etzkowitz & Leydesdorff, 1997), and 'knowledge-based economy' (Leydesdorff, 2006). What these concepts have in common is that the knowledge-production system, or the sciences, has undergone changes which run in parallel with other social and technological developments. The nature of these current transitions is still heavily debated. Should one consider the concepts of 'knowledge economy' and 'information society' merely as rhetorical reflections of the optimism regarding the potential impact of information and communication technologies (ICT) and the Internet during the latter half of the 1990s (Godin, 2005)? David and Foray (2002) argued against using metaphors that suggest a sharp break in the continuity with earlier periods. Shinn (1999) suggests that theories such as Mode 2 of knowledge production and the Triple Helix ignore the fact that change has historically been a constitutive element of science and that current changes can be understood as an articulation of longstanding principles such as conceptual integration, science labour distribution and opportunistic niching (Shinn, 1999). Weingart (1997) argues that Mode 2 of knowledge production captures changes in specific sectors of science (policy-related fields), and that the concept of knowledge society is more useful for understanding processes of 'scientification' of society and 'politicization' of science. We wish to add to this debate by probing further into how certain developments in the knowledge-production system are conditioned by the increasing use of information and communication technologies.

The second set of discussions relates to e-science. The increasing use of ICTs in knowledge production, not only as a means of communication and collaboration, but also, and increasingly, as data, methodologies and types of output of scientific fields, has become the focus of debate within science and science-policy circles. Email is becoming the most common communication medium for scientists (Nentwich, 2003); the Web is providing new means for the formal communication system based on peer-reviewed journals and face-to-face conferences (Vasileiadou, 2001); new fields such as webometrics treat online content and links as data which can provide information about the changing social environment; online repositories have pushed fields such as biomedicine in new directions (Lenoir, 1999). Aspects of this flux of ICTs and their increasing use in science and research have been termed cyberscience (Nentwich, 2003), e-science (Wouters, 2006), computer-mediated science (Heimeriks, 2005). These terms share the assumption that the use of ICTs conditions new types of research environments and have the potential of contributing to new ways of knowledge production. Indeed the establishment of new research institutes and groups devoted solely to the study of cyberscience, e-social sciences, etc. (such as the Virtual Knowledge Studio in the Netherlands, and the E-Social Sciences Programme in the UK) indicate that this assumption is also shared by science policymakers and research-funding agencies. The ways in which ICTs have conditioned changes in the knowledge-production system have hardly been understood or theorized; instead contradicting evidence suggests different possible scenarios. How does the use of ICTs interact with contemporary sciences? How can we understand these changes? The current article aims at contributing to our understanding of these questions by elaborating a theoretical framework for understanding how the use of ICTs conditions developments in knowledge production.

Whether or not the use of ICTs enables new ways of conducting research and transforms the current practices of sciences is still an open debate. Nentwich (2003) has coined the term cyberscience to suggest that the use of ICTs is transforming aspects of sciences, among which the formal communication system, the ways of research collaboration, the type of end result produced. In contrast Gläser suggests that, with the Internet, the social order of scientific communities remains fundamentally unchanged, except for opportunities (in some fields) of communalization at the early stages of data selection, data analysis and data production (Gläser, 2003). Even more sceptically, Hakken rejects the claim that ICTs have changed the way of conducting research (Hakken, 2003). These views are exemplary of the conflicting arguments about whether and how ICTs have transformed the sciences. We argue that these differences are based on different conceptualizations of knowledge production, as well as the lack of a theoretical framework to help us understand contemporary knowledge production. Moreover the scattered empirical studies on cyberscience can be incorporated into a broader theoretical framework such as the one we provide here. The discussion about cyberscience needs to be understood within a broader perspective of a set of changes in society that run in parallel; this will be further elaborated in our discussion section.

Transitions in knowledge production are said to coincide with the growth and development of ICTs and their wide diffusion and application (OECD, 1999). But what is the nature of the interactions between knowledge production and information and communication technologies? Our starting point is that the introduction of ICTs and their increasing use in sciences have enabled the emergence of a new communication environment. More precisely, ICTs and the sciences co-evolve and shape each other in a system of mutual influence (Leydesdorff, 2006). We focus on the perspective of ICTs and how they enable and constrain certain developments in knowledge production, while putting aside the ways changes in knowledge production themselves have enabled the emergence and use of ICTs. The research question behind this article is: *How do the emergence and use of ICTs facilitate contemporary developments in the sciences?*

In order to answer this question and specify the nature of (possible) transitions in knowledge production and dissemination in the information society, we will elaborate a conceptual model that allows us to articulate the nature of changes in the sciences more precisely. The sciences can be described as communication systems embedded in a wider social context, which both shapes and constrains the dynamics of the sciences. The perspective introduced here argues that changes can be understood at three levels (and the interactions between these levels): (a) the local practices of researching, (b) the coordination and control mechanisms at the meso level of scientizing, and (c) the wider landscape of political and societal contexts. This perspective enables us to understand the separate dynamics at the local, global and contextual levels, and how the use of ICTs influences them.

Sciences as three-level communication systems

Science[2] can be seen as a distinctive type of work organization and control, with a focus on continuous novelty and at the same time a strong collective coordination of outcomes (Whitley, 2000). Scientists' work is focused on the production of novel knowledge through the use of distinct methods, data and theories commonly accepted by their community. The novelty of the research output ensures the reputation of the individual scientist and his or her niche in the field. The dissemination of results through communication media translates the 'research output' into a 'body of knowledge' where claims are utilized (accepted, criticized, rejected) by other scientists. The collective coordination of outcomes takes place mainly through the dissemination of the results, which is generally based on a peer-review system, whether the means of dissemination are scientific journals or monographs and books. In addition to the elements of novel ideas and collective coordination, in recent years additional emphasis has been put on the socio-economic value of scientific knowledge in society.

In line with this view, we can understand the sciences as communication systems operating at three interrelated but analytically distinct levels (Rip, 1990). First, the *researching level* (local dynamics) consists of the everyday activities of scientists and researchers in their local context of work: gathering data, fiddling with data analysis, writing up results. We can understand researching activities as comprised of two complementary and symbiotic aspects (Shinn, 1982): the first is the social organization of research, which refers to the ways in which researchers coordinate and allocate tasks between themselves, decide upon research directions, socialize and fight with each other, and communicate with each other; the second is the intellectual organization, which refers to the relationship of researchers with their subject, the role of theory, the type of data and analysis methods. Researching activities take place in specific institutional contexts (e.g. a public research institute or a university department), which in turn influence the type of researching activities. At the same time, these researching activities are combined with the resource management and mobilization strategies that scientists follow in their contexts, as well as the distinct reputational strategies they pursue as an interaction of the field they belong to and the local institutional context (Whitley, 2000).

The second level is the *scientizing level* (global dynamics), which refers to the formal communication activities of scientists, that is the end scientific products published in journals and books, and announced in conferences. This level allows the coordination of scientists in scientific fields. At the scientizing level, knowledge production is a collective and distributed activity in which researchers use the results of others in their field and relate their own findings to the current state of the field (Fujigaki & Leydesdorff, 2000). The formal communications in scientific journals result in the emergence of a system with a stable, accumulative and consistent development of knowledge production (Leydesdorff, 2001). Scientizing activities relate to researching activities insofar as the knowledge production at the former level creates resources for individual scientists, such as recognition and reputation, which feed back into their researching practices in time. Thus scientizing activities can also be seen as distinct ways of managing the local links to institutions, resources and careers (Rip, 1990: 389).

Third, the *politicking level* (contextual dynamics) refers to activities of general mobilization of scientists and scientific communities as social actors in the wider world. Here scientific communities act in political forums, lobby for their interests, and pursue their interests and links alongside and vis-a-vis social, political and economic actors. Politicking activities relate to activities at the local and global levels of mobilization of resources, building career paths and linking to institutions, and are thus interlinked with the scientizing and researching activities. In other words this level relates to all interactions of researchers outside their scientific community. It does not refer to interactions with colleagues and competitors who evaluate and use scientific findings, but rather to relations with society. In this context, processes such as popularization of science, valorization of research and formulation of policy advice are relevant.

As information and communication technologies have become essential tools for sciences, we need to understand their role in the science system and in society at large. This study not only addresses the widespread use and growing capabilities of computers and the linkages they make possible in the areas of communication among scientists, the access to scientific information, scientific instruments and the role of electronic publishing in science; it also addresses the issue of whether these ICT-related developments add up to a fundamental transition in knowledge production. In order to obtain a better understanding of processes of knowledge production and their changes and transitions, we take as a starting point the idea of a research system as we have described it above, a system with its own dynamics of development but one that is also context dependent. In this perspective, knowledge production can be considered as an interactive dynamics at three levels: ongoing research practices on location, that is the micro level of researching; the coordinated interactions of scientists in communications (journals and conferences), that is the meso level of scientizing; and finally the interaction of science and society and the legitimization of science, at the macro level of politicking (Rip, 1990). This allows us to specify in more detail the role of ICTs in knowledge production. It should be noted that the conceptual model represents nested levels that are partially overlapping; the distinctions between the levels are not always clear cut. Furthermore the different levels feed into each other. Despite these complications, the model provides a useful starting point for contributing to the debates about changes in the knowledge-production system and the nature of cyberscience. With its focus on researching practices, collective coordination efforts and the wider societal embeddings, this multilevel perspective provides explanations in terms of patterns that result from changes and interactions.

ICTs in sciences

Local practices: the level of researching

The level of researching practices provides the building blocks for processes of knowledge production, as new ideas, concepts, methods and output are generated at this level. The local context at the researching level consists of small networks of actors that generate novelties on the basis of expectations, visions and skills. The emergence of ICTs, first, provides increasing variation in researching practices by enabling new models, maps and tools to be generated: simulated experimentation *in silico*, algorithms for pattern identification in biomedicine, visualization tools, modelling and simulations have allowed not only new methods of analysis, but also new types of output to be generated (see also Flick, 2002). Robertson (2003) describes how the use of computers has enabled 'mapping' of vast quantities of information and data on an unprecedented scale, for instance in the Human Genome Project or cosmic microwave background radiation. In another context Lenoir (1999) explains the historical emergence of the field of bioinformatics on the basis of the possibilities computers offered. In a number of disciplines ICTs have enabled types of results and scientific output that were not feasible before, given the vast amount of data: output and results based on mapping vast amounts of digitized data and identifying patterns in those data. As Lenoir notes, '[m]ore importantly, as these new tools from information science [ICTs] have been adopted within biology, the conceptual terrain and indeed many of the material practices of biologists have been and are continuing to be radically transformed' (Lenoir, 2002: 115).

Furthermore the topics of research are changing. This relates to what Gibbons et al. (1994) suggest about research in Mode 2 of knowledge production; namely that it focuses more on the properties and behaviour of artefacts (such as computers, models and information) than on natural phenomena in the real world. For instance it would be worth investigating whether recent advances in network theory and network analysis (e.g. in physics and mathematics) are related to the study of the World Wide Web as an object of investigation. Moreover would the use of notions of complex adaptive systems and evolutionary theories in social sciences have been possible without software tools for simulations, which allow for empirical investigation of complex processes?

At the same time ICTs are used also for data collection in fields such as social sciences (online surveys, virtual ethnography), computer science and cybermetrics. This has created new types of discovery environments in many fields (De Jong & Rip, 1997) based on an increased variety of tools, types of data and methods. This variation may result in different types of output as selection mechanisms are reconfigured at the researching level. Should we use online data for the development of science indicators? This was a non-issue two decades ago, whereas today it has reconfigured ways of conducting sociological and policy-related research. In short the use of ICTs has increased variation in the intellectual organization of the sciences, which has already resulted in new types of research questions, new types of scientific output, and new types of methods and tools for inquiry.

This variation in intellectual organization also entails an element of risk. In a previous study of a distributed, interdisciplinary team which used ICTs as data and aimed at developing ICT-based tools and methods, we found that the innovative element of its intellectual focus – the fact that the team was investigating unexplored intellectual territory, one that is as fluid and non-standardized as ICT-based data (hyperlinks, online content) – proved to be a risk factor in the operation of the team (Vasileiadou, forthcoming). The use of ICTs as data, data-gathering tools, data-analysis methods, data-visualization methods and types of output increased the variety of possible output of the team, but it also increased uncertainty in the team, since work procedures were heterogeneous and the format of the outcomes uncertain. The team faced high task uncertainty (Whitley, 2000) and therefore risk because ICTs were its subject matter. This high task uncertainty is the other side of the coin of increased heterogeneity of output.

In addition the use of ICTs as data, data-analysis tools and visualization tools may transform the relationship between the researcher and his/her subject matter: this relationship does not need to be bound by spatial–temporal dimensions: simulated experimentation, chemical reactions *in silico*, virtual ethnography, algorithms to identify patterns in genes. Being an anthropologist entailed, until now, going to a physical location as an observer (participant or not) and studying behaviour in real time. For a virtual ethnographer, the physical contact is with written text, images or sounds online (Hine, 2000). What part of the identification of an anthropologist related to being in contact with people and observing human behaviour (Gupta & Ferguson, 1997)? Is a chemist still a chemist if most of the experimentation is conducted in a virtual space? This distancing of the individual researcher from the subject matter may in some fields decrease the role of 'discipline' or 'subject matter' or 'intellectual topic' in the individual identity and may create different socialization mechanisms in research, as different skills and competencies become more relevant. Thus virtual ethnographers may have more in common with computer scientists, in terms of capacities and skills, than with traditional ethnographers. The complex nature of this change is also evident in the use of computer simulation in science and engineering (Warnke, 2002). On the one hand, the knowledge generated through computer simulations requires less direct contact with the subject matter in the form of real laboratory experiments. On the other hand, the possibility to visualize the results of computer simulations allows for an easy transfer of insights on highly complex processes even to laypersons. For the scientist or engineer visualization enables a much more intuitive understanding than tables and diagrams resulting from traditional methods.

The wide variety of ICTs clearly impacts on the local practices of researchers in the form of the local use of email and the development of tools. In another study we conducted, we investigated the role of online and offline means of communication for research teams (Heimeriks, 2005). Our results indicated that ICTs play an important role in obtaining (information) resources and in enabling the general and informal communications (mainly local) associated with researching. Therefore ICTs influence the social organization of research, first, by allowing a different coordination and task allocation that is less geographically bounded and potentially international. Even though distance still matters (Olson & Olson, 2000), it is becoming less relevant in the collaboration decisions of researchers (Nentwich, 2003; Van Oort et al., forthcoming). The decreasing importance of distance is also promoted by national and international research-funding schemes, such as Framework Programmes of the European Commission.

Another change at the researching level relates to the practices involved in the codification of previously tacit knowledge by means of information technologies. In many fields the use of ICTs for knowledge generation and exchange requires the transfer of knowledge into certain formats. For this purpose previously 'tacit' or 'implicit' knowledge needs to be captured in an explicit way and therefore to be transformed. For example in engineering, a number of experience-based 'rules of thumb' needed to be translated into mathematical equations to be used within mathematical models that form the basis for computer simulations. Also on a shopfloor level, control paradigms based on staff experience were replaced by mathematical models so as to allow for the implementation of computer-based control. Once formalized, the possibilities for combining, rescaling, reshuffling, reformatting (e.g. into suggestive visualizations) and exchanging knowledge with little time and effort are substantially increased (Warnke, 2002). In this way ICTs function as 'inscription devices' (Latour, 1987) enabling powerful 'mobilization' of knowledge. This increasing codification of tacit knowledge seems to become more relevant as data in many fields become digitized, more mobile and interchangeable. Digitization of communications also changed the nature of interactions between science and society, giving rise to intervention by different types of institutions, and creating new economic and political dynamics in science, as we shall describe in the discussion of the politicking level.

This visibility and codification of previously informal and tacit knowledge, and the use of ICTs for recording has another implication as well. The use of ICTs makes the informal processes of research collaboration traceable and visible: processes that took place in the lab corridors before, such as socializing and exchanging pleasantries, decisions about research tasks, disagreements about roles and responsibilities. This visibility of informal processes can contribute to the emergence of a collective identity at the researching level which is less bound by spatial–temporal coordinates (and often disciplinary boundaries). In this sense a geographically dispersed collaborative endeavour can become a research team, with a shared identity (Vasileiadou, forthcoming), with the use of emailing lists and online communications as collective memory (see also Brown & Lightfoot, 2002). This means that the use of ICTs has enabled the emergence of different types of identities at the researching level: shared identities not necessarily bound by locales, or even the disciplinary confines that the locale (e.g. a specific lab) entails. One may even suggest that it creates researchers, not scientists. Processes of open innovation provide an interesting analogy here, as more and more R&D

organizations develop an identity that is increasingly and consciously inclusive, incorporating a heterogeneity of users and other organizations. These ideas will be developed in the following subsection.

All the aforementioned ICT-related developments on the researching level arise in parallel with existing ('traditional') practices. Current research suggests that the use of ICTs adds more variety to knowledge production at the local level, but the new modes of researching activities only partially replace existing research activities (Nentwich, 2003). ICT enables additional models, modes of communication and outputs on top of and in addition to traditional activities. For instance, as a means of communication, the use of ICTs is an added possibility alongside more traditional means such as face-to-face meetings. Moreover the use of ICTs as data (e.g. Web-based indicators) stands alongside traditional indicators. Furthermore ICTs are used in very field-specific ways to generate the tools, data, reports and other types of output that fit the research tradition (Barjak, 2004). In short, if we consider researching as a communication system, in which nodes are connected in a network, not only the nodes but also the links are open to change (depending on the local expectations, visions and skills as well as on the existing research tradition) because of the use of ICTs.

Summarizing: the use of ICTs at the researching level allows for a heterogeneity of the types of output produced, a variety in the methods, tools and concepts to be developed, a different type of relationship between the scientist and the subject matter, and different socialization and identity-construction mechanisms for scientists. Now we turn to the scientizing level in order to investigate how these developments feed into processes there.

Collective coordination and control: the level of scientizing

Scientizing refers to the communication activities of scientists that result in the formation of disciplinary identities. At this level knowledge production is a collective and distributed activity in which researchers use the results of others in their field and relate their own findings to the current state of the field, thus giving rise to a stable community. Until now the print-based communication system has provided the basic elements of disciplinary identity construction. As Fujigaki & Leydesdorff (2000) point out, advanced scientific knowledge production in traditional fields usually results in the submission of publications to scientific journals. This specific form of quality control is maintained by the scientific community (quasi-) autonomously because it has functions for the development of the science system itself. The quality control of these products of scientific knowledge is achieved by the review system used by the journals. The legitimacy and validity of knowledge is controlled and reinforced through the process of judging whether or not submitted papers can be accepted. By analogy, in monograph-based and book-based fields, editorial guidance plays the role of control mechanism.

These processes also apply to so-called 'interdisciplinary fields'. Fully developed interdisciplinary fields are characterized by a journal-based communication system very similar to the communication patterns of traditional disciplinary fields. Interdisciplinary fields use elements of other disciplines but organize them in a specific way. The fields that emerge in this way are 'interdisciplinary' only from the perspective of the traditional disciplines but have a similarly closed communication network as disciplines. In this sense disciplinarity is an organizational rather than a cognitive description of fields (Van den Besselaar & Heimeriks, 2001; Heimeriks, 2005).

Nevertheless ICT-related disciplinary differences can be traced in recent developments in the formal publication system of science. The emergence of various formats for online journals (see Kling & McKim, 2000)[3] has created new opportunities and tensions in sciences. These journals have destabilized the institutionalization patterns of formal scientific publication, opening up the sphere of production, publishing and diffusion to new smaller-scale participants (e.g. individual scientists, minor scholarly societies, etc.) as well as opening up new issues for a renegotiation of power between scientists and publishers, such as copyright management and new filtering mechanisms. New formats of commodification, of preservation and archiving, and reproduction are altering traditional balances (Vasileiadou, 2001) and bringing new players (e.g. Google Scholar, Scopus) into the field. The electronic revolution in the journal system has opened up new possibilities and tensions in other aspects, which have not yet stabilized in most fields, even though most online journals follow the same format and procedures as their print equivalents (Roberts, 1999). Indeed the similarity of most e-journals to print journals and the retention of their main features points to the essential role of print-based communications for the constitution and coordination of scientific communities until now (Gläser, 2003). So far electronic publishing has provided an additional layer of communication rather than destabilizing the role of existing journals.

The question of how the emergence of ICTs additionally influences the formation of scientific communities is still open. Elsewhere we found that there are enormous disciplinary differences with regard to Web-based communications (Heimeriks, 2005). We collected data on several dimensions of online communications, the shared set of hyperlinks of the departments, and the characteristics of the websites in terms of size and types of files. The results suggest that Web-based communications play a role in obtaining financial and information resources, the use and exchange of digital data, the dissemination of results to academic audiences and the dissemination of (non-traditional) output. The Internet especially contributes to the interaction with non-academic partners, the dissemination of non-traditional output (software tools, visualizations, etc.) and the use of digital data. However, these characteristics can be traced in different Web attributes in each field. There is no systematic relationship between the use of various Web-based communications. For example the importance of online communications in the field of astrophysics is indicated by the sheer size of the websites, and the large quantity of digital images and video files they contain. The large number of applications found on information-science and AI websites indicates a strong importance for ICTs in the researching practices of these fields. In general these analyses established the existence of distinct online communication patterns, related to field-specific digital data and output.

Furthermore the availability of additional electronic information resources and databases (as well as increased reflexivity about the information) provides new opportunities for the formation of fields and disciplines. As pointed out at the researching level, ICTs can link geographically separated researchers and help them locate interesting or compatible resources. Scientific emailing lists and specialized online forums have the potential to bridge gaps and unite geographically dispersed scientists, creating communities based on other than the print media. The Association of Internet Researchers (AoIR) is an example of a community (with its own conferences, book volumes, ethics-codification processes) not based on the journal system but organized around an emailing list. Identity-formation mechanisms for fields and subfields do not necessarily rest upon the print medium. The relationship that researchers entertain with the history of their field is also expected to change; researchers' perception of their field (and its history) may become increasingly dependent on an ever-expanding reservoir of ICT-mediated scientific content. The availability of email archives, pre-print servers and online databases affects the formation of field identities by creating a bias towards the traceable information captured in these new media. These changing dynamics are associated with more rapid and heterogeneous changes in the formation of fields, with the parallel tendencies of balkanization and globalization of scientific communities, which are articulated with different configurations in different (emerging) fields.

These developments reinforce developments at the local, researching level. In a world where knowledge and information are paramount, researchers need new skills in order to adapt to rapidly changing environments. Not only are digital literacy and e-skills in themselves becoming essential, the tacit skill of reflexivity is also increasingly crucial. The availability of digital-information resources and databases creates more need for researchers to be reflexive about the value of information, how it can be recombined with other information, in which context the information is meaningful and how it could be processed, stored, communicated and analysed. As pointed out, ICTs allow for less geographically bounded, and potentially international, collaborations. ICTs, however, also have the potential to fragment interaction and divide groups by leading people to spend more time on specialized interests and by screening out less preferred contacts (Van Alstyne & Brynjolfsson, 1997). Consequently, both 'informationally' and 'socially', researchers need to be more reflexive in order to be successful. In this context the social sciences and humanities are expected to play an increasing role because they reflect and organize the self-representation of science and society (Leydesdorff, 2006).

Moreover the increasing use of ICTs at the scientizing level feeds into changes in the researching practices of career choices and reputation building, thus giving rise to different dynamics of identity formation for scientific communities. Scientists' visibility does not rely exclusively on the number of publications and their peer citations but can increasingly result from a well-designed and well-linked homepage providing scientific content. The Web and the visibility it provides to a wider audience increasingly become resources strategically managed by scientists in their positioning. Publication of an article in *First Monday*[4] may result in thousands of hits and/or downloading by a heterogeneous audience, whereas a publication in a highly prestigious print journal can at best result in a limited number of citations. What trajectories do scientists follow with respect to their publication strategies? Even though problems of institutionalization and standardization of e-journals persist (Roberts, 1999), the Web provides different possible career paths and resources for individual researchers and their local institutions.

In parallel with the journal-based processes of scientizing, ICTs have facilitated new ways of accumulating and controlling knowledge. The dramatic rise of ICT as an enabling technology has been making possible new modes of inter-party cooperation upon which knowledge accumulation relies. For a process of knowledge accumulation to function properly, there is need for a networked information structure that creates the possibility of selection and feedback. In this way a collective and distributed system can emerge, in analogy with the journal system in which researchers can use the results of others in their field, and partly accept, partly modify and partly reject them. Examples of these coordinated efforts of collective knowledge accumulation and control are open-source software projects, servers of working-papers and the online encyclopedia Wikipedia. Open innovation processes are also exemplary of these developments. Organizations can better gain insight, at an earlier stage, into innovative ideas, knowledge and technologies by opening up to the outside world than by relying solely on their own sources. This process is enabled by the use of ICTs in new types of contexts such as the Living Labs.

In conclusion, the journal-based communication system (whether paper based or online) still has a dominant role in disciplinary identity construction and its associated mechanisms of quality control and accumulation of knowledge. In addition, the use of ICTs at the scientizing level enables new ways of collective coordination of scientific communities, leading to different possible identity-formation mechanisms, and diversifies the types of rewards available for individual scientists, thus impacting on their career-path strategies and the resource management of their local contexts, even as it allows for accumulation of knowledge on the basis of different mechanisms than the print-based journal system. These mechanisms create new challenges but also tensions for individual scientists as well as scientific fields and their institutions; and the way these issues will stabilize in each field is expected to be very distinct.

Contextual dynamics: the level of politicking

Politicking refers to processes of interaction, between science and society in general, which have always been characterized by co-evolution. Indeed the boundaries of the science system are fuzzy, and even more so today than at previous times, with the proliferation of scientific intermediaries (Vasileiadou & Van den Besselaar, 2006), the need for social accountability of the sciences (Nowotny, Scott & Gibbons, 2001) and the increasing interactions at the boundaries of the industry–government–university system (Leydesdorff, 2006). However, the ICT-related transitions on the previous two levels create new dynamics at the interface between science and society. Again we should stress that changes at the researching level, the scientizing level and the politicking level feed into each other in patterned ways.

Recent changes at the politicking level include the production of knowledge in more locations, outside the traditional research sites such as universities and research institutes, and the involvement of new societal actors in the creation, maintenance and utilization of scientific databases (e.g. Gibbons et al., 1994; Etzkowitz & Leydesdorff, 1997). In addition the growth of knowledge production in new areas and locations has been encouraged by the increasing tendency of states and other organizations to rely on formal knowledge for dealing with complex problems. Reinforcing these developments, the introduction of digital information, online databases and the Internet have enabled a radical lowering of costs related to information dissemination, both in pure form and black-boxed in technologies. Furthermore, as described, new ICTs facilitate new ways of accumulation and therefore control of knowledge (Poster, 1994).

Electronic media have created new means of access to knowledge produced by research groups for a variety of users, companies, policymakers and NGOs, thus resulting in a more 'public' science. Moreover ICTs can be used to study these developments as well. These heterogeneous users can be traced by mapping the online communications of research groups. In a previous case study, which mapped the electronic and non-electronic communications of a research group, we established that non-electronic media (e.g. journal publications) function mainly within the disciplinary network of collaboration inside the research community. In contrast electronic media enlarge the network to the users of knowledge. Furthermore these users were traced by looking at the inlinks and log-files of the website (Heimeriks, 2005).

These developments not only coincide with the increased possibilities for interaction and feedback that ICTs made possible, they also relate to the increased availability of data and processing capacities at the researching level. These new digital data create – and at the same time provide an answer to – new needs for more evidence-based information for political and economic purposes. Or, as Leydesdorff (2006) puts it, the systematic organization of knowledge production and control increasingly provides a third coordination mechanism to the social system, in addition to the traditional mechanisms of economic exchange and political decisionmaking. The codification of tacit knowledge discussed at the scientizing level has strengthened this as economic and political actors have come to occupy an even stronger position above organizations' knowledge. Research bodies are organizing their knowledge production in a more integrated and cyclical fashion, and including feedback moments and decisions regarding the flow of input.

In addition the digitization and accumulation of different types of knowledge and data discussed in the previous sections have resulted in their increased mobility and utilization in different contexts. The development and consolidation of national or international social sciences and natural sciences databases are exemplary of these processes. For instance in the field of genetics, hyperlinks to international data repositories have a prominent role in the websites of research groups (Heimeriks, 2005). Grey-literature discussions and possibilities are also linked to the utilization of digitized knowledge in different contexts, with the emergence of new actors in the field.[5] The resources needed for such projects, as well as the need for standardization, development of metadata and utilization prospects, have given rise to new opportunities for actors outside academia (publishers, statistical offices, governmental institutes) to be involved in these developments. Thus the use of ICTs for digitization and accumulation of data and tacit knowledge has enabled new types of linkages between academia and other institutions, and has enabled the institutionalized use of data and the codification of related practices such as ethics of data recording and use.

While ICTs make the codification of previously tacit knowledge possible, they also present new challenges. Codification involves the exteriorization of memory and thus relies on media such as ICTs to exist independently from individuals. ICTs also create new types of problems for the scientific community, especially with regard to preservation in time. Rapid software advancements that make previous standards obsolete, limited stability of URL names and frequent disappearance of pages are but a few of the problems encountered online (Wouters, Hellsten & Leydesdorff, 2004). As a medium, the Web has a dynamic nature: sites disappear, pages undergo changes (Brewington & Cybenko, 2000), pages go 'comatose' (Koehler, 1999), many new ones are added every day, links break. As Koehler (1999) notes: 'World brain [the Internet] has short memory. And when it does remember, it changes its mind a lot.' Preservation of scientific content (e-journals, online databases, e-print archives, etc.) is another issue that requires a high degree of institutionalization, and it potentially enables institutes, governments and publishers to get involved with and influence scientific practices in new ways.

The process of politicking thus is a co-evolution of increased linkages, shifting power balance between science and society, increasingly effective feedback mechanisms, increased availability of digital data and increased knowledge needs on the part of policymakers and society. These processes represent the interaction between science and society in a context of application involving heterogeneous actors like companies, policymakers and societal organizations (Gibbons et al., 1994; Etzkowitz & Leydesdorff, 1997). The politicking level, moreover, relates to and influences developments at the researching level described above. A variety of agencies (such as the European Commission) formulate and support knowledge production that is application-focused. This involves the establishment of interdisciplinary research teams and peer-group communities by a variety of non-scientific organizations. Such research teams possess heterogeneous skills, are generally short-lived, have different development of stable authority structures and are based in a variety of organizational locations. Research quality and intellectual significance are judged by a variety of standards, such as field-specific societal relevance (Sharp, 1998; Georghiou, 2001). In this process of politicking, an evolutionary selection – based on socio-economic criteria – occurs that involves non-cognitive standards to assess the usefulness and desirability of ideas (Fujigaki & Leydesdorff, 2000; Frederiksen, Hansson & Wenneberg, 2003).

In short, ICT-related developments at the politicking level include the increasing possibility for interaction between universities, scientific communities and other societal actors, such as governments, private companies and NGOs, on the basis of a variety of mechanisms: database establishment, increasing need and reliance on theoretical knowledge, societal assessment of relevant knowledge. The use of ICTs has enabled and increased direct links between the scientific community and a heterogeneous set of actors (Leydesdorff, 2006), thus introducing new uncertainties and new possibilities into the system.

Discussion and conclusion

The above analysis does not present new empirical work, but it does incorporate the findings of previous empirical research within the context of the conceptual framework that we propose. Some of the developments it highlights have not yet been researched fully: for instance the extent of changes in researchers' career paths, or advances in network theory and network analysis facilitated by the study of the Web as a research object. These topics offer fruitful directions for further research. In this sense the article also aimed at opening up new research questions. Nevertheless the main objective was to propose a conceptual framework that helps us understand current developments in sciences and ICTs.

We began by addressing the different ways in which knowledge production and ICTs have co-evolved in the information society. Based on empirical studies and theoretical conceptualizations, we proposed a framework for understanding changes in knowledge production that are facilitated by the emergence and use of ICTs. The current transitions in knowledge production and dissemination can be conceptualized as an interaction at three levels. At each level the rise of ICTs has added variety and heterogeneity in modes of communication, types of output, forms of collaboration, potential users and involved institutions. How does the analysis presented here relate to the two debates we sketched in the introduction? How do the emergence and use of ICTs facilitate contemporary developments in the sciences?

The latter question can be answered with reference to the researching level of the analysis. The main contribution of ICTs is the emergence of heterogeneity in methods of analysis, types of data, types of scientific output, modes of communication and coordination, modes of socialization and identity construction, types of career paths. This heterogeneity provides input at the scientizing and politicking levels, where it results in an additional layer of scientific communication, identity-construction mechanisms, linkages between science and society, and modes of science-quality assessment. The additional layer of communication that the ICTs provide in the sciences changes the dynamics of established layers of communication (such as the journal-based system), first, by providing a variety of new elements that can be recombined with more established elements. Thus using email to support research collaboration has resulted in a recombination of elements of social and intellectual dimensions of research in a way that is no longer discipline prescribed (Vasileiadou, forthcoming). Second, the heterogeneity that emerges from the use of ICTs results in increasing reflexivity about established modes of communication; and discussions about, for example, e-publishing and intellectual copyright can be understood in this way. Therefore the additional network of relations generates reflexive subdynamics that continuously reorganize the underlying infrastructure in order to optimize communications (Etzkowitz & Leydesdorff, 2000).

This heterogeneity is in part related to the diverse nature of ICTs themselves and their use in different processes (data collection, analysis, publication, communication, etc.). ICTs are a heterogeneous collection of media and tools with different dynamics, network structures, communicated content and impact. In addition this heterogeneity is related to disciplinary needs and traditions. The variety of data-analysis tools, data storage, processing capacity, software tools, information-delivery technologies and electronic networks creates a heterogeneity that is (partially) adopted in ways that reflect different field-specific patterns and needs. Therefore, in each field, the researching environment, the formation of disciplinary identities and the interactions with society are changing in different ways through the use of ICTs (Heimeriks, 2005). Clearly there is not one transition occurring across all fields. Finally, this heterogeneity is also emerging from the interactions at the interface of each level. The emerging configurations arise from a co-evolution of ICT-related changes at each level, such as increased linkages and interactions, increasingly effective feedback mechanisms, increased availability of digital data, data processing and increased knowledge needs on the part of policy and society.

This heterogeneity, the additional layer of communication that ICTs provide, may furnish a useful perspective on the two debates in which this article was introduced. The second debate, about the extent to which e-science or cyberscience is a qualitatively different way of conducting science, can be explained in relation to the analysis provided here. Most advocates of e-science or cyberscience commence with transitions at the researching level, where this heterogeneity is more evident: new types of data, methods and output, as well as new modes of communication and collaboration, have emerged in different fields (Finholt, 2003; Nentwich, 2003). The critique at the researching level relates mainly to problems that this heterogeneity entails, for example, problems of conducting research at a distance (Olson & Olson, 2000). At the scientizing level, however, established coordination mechanisms, such as the peer-review system of journals, still persist, and ICTs provide, as we showed, an additional layer. Indeed most sceptical voices in e-science refer to the scientizing level of analysis (Kling & McKim, 2000; Gläser, 2003). Therefore the debate needs to be understood as addressing different levels of analysis.

The debate about the nature of changes in the knowledge-production system in the last decades gave rise to concepts such as Mode 2 and Triple Helix, which attempt to capture sides of this increased heterogeneity. The Mode 2 diagnosis suggests that these heterogeneous (and field-specific) features create a transition from Mode 1 to Mode 2. The variety of actors involved in knowledge production in biomedicine is not an element that can equally describe developments in anthropology. However, in that field, the heterogeneity results in reflexivity with regard to the field, the topics and the methods of inquiry. The current transitions in sciences, therefore, can be better understood as additional heterogeneity, which translates into different combinations of new and established elements in each field. At the same time, the Triple Helix model provides a way to understand the tensions arising from science–society interactions, mainly at the politicking level. New knowledge production and communication continuously disturb the political economy and the market equilibrium (Leydesdorff, 2006). The analysis offered here puts these tensions in the perspective of simultaneous changes of and feedback from the researching and the scientizing levels as well.

These tensions find their roots in situations where researchers are increasingly aware that the same knowledge can have a different value for other audiences; that information is provided with meaning during communication; and that possibilities for further communications can be interfered with by unexpected feedback. Furthermore ICTs have opened up new possibilities for generating concepts and ideas. The increased reflexivity that has been enabled by ICTs is further reinforced by the permanent traceability and visibility of ICT-based interactions that were previously absent from informal and non-codified communications. The interface between science and society is changing; and in this co-evolution of the growing importance of ICTs and the increased reflexive awareness of the contextual value of knowledge in a complex society, the need for the growth of knowledge production in new areas and locations has been encouraged by states and other organizations, further adding to the complexity. The Mode 2 diagnosis and related concepts of radical discontinuity (Shinn, 1999) incorrectly suggest that these features add up to a new and stable mode of knowledge production.

From a policy perspective the analysis presented here has several implications. In a knowledge-based society, most societal problems require new knowledge developments, and thus 'problem-based' R&D will become more and more important and encompassing. In addition more and more social actors (different ones in each field), beyond the usual R&D stakeholders, wish to be involved in such debates. Given the diversity of configurations that evolve from interactions between changing researching environments, changing formation of disciplinary identities and the increasing interactions with society, the 'one size fits all' answer is becoming increasingly obsolete. Policymakers can no longer apply the same framework and instruments to different research configurations. Policies that ignore the characteristics, dynamics and requirements of different configurations across fields may be ineffective or even harmful. It is necessary to understand the networked nature of the research dynamics in each field, its geographical distribution and the types of organizations that are involved. Concepts such as the Mode 2 of knowledge production can be interpreted as a reaction to the increasing tension (and increasing awareness of this tension) between the interconnected subsystems.

Our conceptualization explains why these tensions need not to be resolved. When we define the three levels as a field-specific configuration that co-evolves from the changes at each level, a resolution would hinder the dynamics of interactions among its levels. So rather than constructing a simplified stereotype of knowledge production and then implying that Mode 1 has been supplanted by Mode 2, it seems more useful to embrace the heterogeneity and complexity emerging in knowledge production because of the emergence and use of ICTs.[6]

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Notes

1. The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.
2. In this paper we use the words 'science' and 'sciences' in the most inclusive sense, e.g. we refer to knowledge production in all fields of natural sciences, social sciences and humanities.

3. They distinguish between electronic journals (e-journals), electronic working papers, hybrid paper–electronic journals (p–e-journals) and hybrid electronic–paper journals (e–p-journals), on the basis of the technical means of primary distribution (hence the paper–electronic vs. electronic–paper distinction), as well as on the existence or not of the peer-review function in publication (hence the distinction between journals and working articles).

4. Online journal available at www.firstmonday.org/.

5. See for example the GreyLIT Network, supported by a number of US Federal Agencies, such as the Department of Energy, the Defense Technical Information Center, and US Environmental Protection Agency.

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