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# Addressing the dynamics of science in curricular reform for scientific literacy: the case of genomics

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# Addressing the Dynamics of Science in Curricular Reform for Scientific Literacy: The Case of Genomics

## *Abstract*

Science education reform must anticipate the scientific literacy required by the next generation of citizens. Particularly, this counts for rapidly emerging and evolving scientific disciplines such as genomics. Taking this discipline as a case, such anticipation is becoming increasingly problematic in today's knowledge societies in which the dynamics of the natural sciences is unprecedented. This raises the question how scientific literacy can be defined in order to appropriate the dynamics of natural sciences such as genomics. Drawing on a contemporary socio-cultural perspective on the dynamics of science, the science education research literature is briefly reviewed in this respect. It is argued that scientific literacy captures the dynamics of science once defined as an emergent feature of collective activity. This requires a form of science education to which the learners' agency is central. The implications of this thesis will be discussed in regard to the case of embedding genomics in science curricula.

# Addressing the Dynamics of Science in Curricular Reform for Scientific Literacy: The Case of Genomics

The broad aim of science education is scientific literacy: The forms of knowing students will require as citizens in a scientifically and technologically sophisticated society of tomorrow. In contemporary knowledge societies, the production of scientific knowledge is increasingly reflexive, transdisciplinary, and large-scaled (Nowotny, Scott & Gibbons, 2001). This inherently increasing dynamic of science faces us with the problem that the scientific knowledge students are equipped with in schools is getting out of pace with the scientific knowledge as it is produced and applied in other parts of society. Particularly, this counts for and is already observable in the case of the relatively new discipline genomics. The speed by which this field of study is emerging is confronting citizens with new questions while they go about in their daily and professional lives. How can we design science education in a way that fosters scientific literacy among the next generation of citizens who are continuously being confronted with new emerging disciplines such as genomics?

At the heart of the problem laid down here is the question what we mean with scientific literacy. Indeed, what scientific literacy is taken to be depends very much on the conceptions of science discursively associated with it. If scientific literacy is defined in terms that fail to grasp the dynamics of a science such as genomics, then students cannot be properly equipped with the knowledge they will require as citizens in scientifically and technologically sophisticated societies from which genomics emerged. This raises the question whether and how definitions of scientific literacy appropriate the dynamics of a science such as genomics. Taking genomics as a special case, then, this study briefly reviews the science education research literature in this respect.

In what follows, this paper will take five turns. First, I introduce briefly the science of genomics as a case of a rapidly evolving and hence inherently dynamic science. Second, I introduce actor-network theory as a socio-cultural framework to grasp the dynamics of sciences such as genomics in contemporary knowledge societies. Third, drawing on this theoretical frame, the science education research literature will be reviewed. The aim of this review is to understand how definitions of scientific literacy address the dynamics of sciences such as genomics. I maintain that the dynamics of sciences such as genomics are appropriated by a definition of scientific literacy as an emergent feature of collective human activity. Fourth, I argue that scientific literacy understood as a collective entity requires science curricula to which the learners' agency is more central than is the case in current science education practices. Drawing on this argument, fifth, I discuss the implications for genomics education and further research.

## ***Genomics as a Case of the Dynamics of Science***

Genomics is the study of the structure, function, and evolution of genomes in all kingdoms of life. The word 'genome' results from merging the word 'gene', which refers to a unit of the genetic material of an organism coding for a protein (DNA or RNA), with the generalized suffix 'ome', referring to an entire collectivity of units. However, a genome is usually considered more than only the set of genes of an organism. All the genetic material in the chromosomes of a particular organism make up its genome; its size is generally given as its total number of base pairs of the set of DNA or RNA molecules found in its chromosome(s). The field of genomics emerged in 1977 after Fred Sanger and his co-workers determined the sequence of the 5,368 base pairs of the DNA molecule that makes up the entire genome of the virus *Bacteriophage Φ-X174* (Sanger et al., 1977). Although the genomes of a number of other organisms—mostly viruses—were 'sequenced' during the early 1980s, the sequencing of genomes really got impetus once the worldwide Human Genome Project started in 1988, which finally resulted in a rough draft of the human genome in early 2001. Because of better techniques that became available at the time, the number of ‘sequenced’ genomes of other organisms rapidly increased, including those of *Escherichia coli* (a bacterium found in human intestines), yeast, rice, and mouse. As of January 26, 2009, the number of complete sequences was known of about 3231 viruses, 2197 bacterial species and roughly 383 eukaryote organisms, of which 159 animals, 59 plants, and 112 fungi (NCBI, 2009a, 2009b).

Despite a historical focus on the sequencing of genomes, the scope of genomics is currently much wider. For instance, the knowledge of full genomes has created the possibility for the field of *functional genomics*. This is the branch of genomics that is concerned with understanding which genes are expressed under which conditions in which parts of the organism. More so, the emergence of sophisticated technology within the field of genomics such as genome mapping, data storage, and data analyses has generated a spin-off that generated entire new sister disciplines of genomics and radically changed existing disciplines. One example is the field of bioinformatics that is concerned with processing the huge datasets that come available as a result of sequencing genomes consisting of milliards of basepairs. Another example is the study of proteomics, which applies the technology of genomics to understand which proteins are at work under which conditions in which parts of organisms. The knowledge and technologies generated in these new and rapidly evolving disciplines of the life sciences is nowadays applied to solve challenging problems in biology and medicine. For instance, systems biology is one of the youngest disciplines in biology and which is concerned with the integration of complex data about the interactions in biological systems from diverse experimental sources using interdisciplinary tools and personnel created by genomics.

As a result of its rapid evolution during the past twenty years, genomics is a science that can be considered highly dynamic (Braam, in press). Indeed, it is exemplary for the dynamic way in which scientific discipline currently emerge and evolve in contemporary knowledge societies. Inherent to this dynamic is an increasingly reflexive, transdisciplinary, and large-scaled production of scientific knowledge (Nowotny, Scott & Gibbons, 2001). Reflexivity is made possible by the use of sophisticated databases easily accessible by the internet. Thus, the findings of one branch of genomics are often instantly taken up by other branches of genomics, which can be considered a driving force of the discipline of genomics. Transdisciplinarity is a *conditio sine qua non* for solving challenging problems in biology and medicine. This is so because several traditional scientific disciplines are involved with the application of techniques and understandings made available by genomics, such as biochemistry and molecular biology to understand the interaction between macromolecules involved with genomes, mathematics, and informatics for processing the huge data sets made available by sequencing. This counts especially for the sister branch of systems biology, in which the main aim is to bring together the different disciplines to generate meaning from the huge datasets that branches such as genomics and proteomics yielded. More so, each contribution to genomics from traditional disciplines brings in particular stakeholders that also have an interest in the research projects involved, such as the agro-industry, medicine, several governmental and non-governmental organisations, and branches concerned with safety and security.

The dynamics of sciences such as genomics add another component to science education's major aim to foster scientific literacy among the next generation of citizens. As a result of this dynamics, the next generation of citizens will continuously being confronted with new emerging disciplines such as genomics, confronting citizens with new questions while they go about in their daily and professional lives. In other words, the evolution of sciences such as genomics requires a science education that aims at literacies that are defined in a way that it appropriates the inherent dynamics of the scientific knowledge production involved. This raises the question how the dynamics of science can be appropriated more generally, that is, theoretically.

## *Capturing the Dynamics of Science*

The dynamics of science is a rather young research topic. Sparked by a sociological turn in the philosophy of science (e.g., Kuhn, 1970), researchers became interested in what scientists actually *do* and how their actions shape scientific knowledge. Since the late 1970s, an increasing number of studies were setup with the aim to monitor how scientists go about in their everyday work in laboratories, at conferences, and in the field. In domains such as molecular biology (Latour and Woolgar, 1986), high energy physics (Traweek, 1988), and biochemistry (Knorr-Cetina, 1981), social scientists produced ethnographies of the manifold and complex ways in which natural scientists produce scientific knowledge. Collectively, these ethnographies undermined the possibility of any logical reconstruction of the processes legitimating scientific theories that philosophers of science such as the logical positivists were after. Put shortly, it appeared that the 'scientific method' is a myth. Simultaneously, scholars in this discipline developed socio-cultural frameworks that allowed a better understanding of the dynamics of science than a logical reconstruction based on ready-made science.

One—if not the most—common framework for understanding the dynamics of science is Actor-Network Theory (ANT). One of the key theses of this theory is that 'scientific content' reflected by concepts such as 'DNA' and 'genome' cannot be reduced to human cognition entirely. Some understanding of this thesis and its implications for the humanities is required for understanding my study and the models I use therein. However, using ANT as a theoretical frame for understanding the dynamics of science is still uncommon in the community of science educators. Therefore, I provide here a short introduction to ANT.

ANT resulted from attempts to reveal the dynamics of the infrastructure that constitutes the often-static accounts of scientific and technological achievements (Latour, 1987; Callon, 1991). This theory takes account of the given that *science-in-the-making* develops dynamically in time and space and cannot be described by temporally and spatially static elements discursively associated with the *ready-made science* one may find, for example, in science textbooks. These static elements commonly reduce accounts of scientific and technological artefacts to categories that are either natural (the things ‘out there in the natural reality’ discovered by scientists), social (the ‘heroic’ scientists), or discursive (abbreviations such as DNA and other texts that can be commonly found in science textbooks). Hence to describe how science-in-the-making occurs, they developed a non-reductionist approach by taking into account simultaneously all categories (social, natural, discursive) that were hitherto considered independently. Pivotal in this approach is the idea of *actor-networks*, which merges two terms—actor and network—usually featured as opposites in the social sciences. However,

> […] it is not just another attempt to show the artificial or dialectical nature of these classical oppositions. On the contrary, its purpose is to show how they are constructed and to provide tools for analyzing that process. One of the core assumptions of ANT is that what the social sciences usually call ‘society’ is an ongoing achievement. ANT is an attempt to provide analytical tools for explaining the very process by which society is constantly reconfigured. What distinguishes it from other constructivist approaches is its explanation of society in the making, in which science and technology play a key part. (Callon, 2001, p. 62)

Focusing on the constantly reconfiguration of society—the society-in-the-making—allows us to understand the dynamic of science and technology as playing a key role therein. This holistic approach is characterized by the absence of a presumed boundary between nature and culture. Thus, there is the premise of symmetry between human actors and nonhuman participants (artefacts, ‘natural’ entities) in the way they act and are acted upon in actor-networks. For instance, both Francis Crick—one of the discoverers of the genetic code—and DNA can be considered *actants* in the developing actor-networks that constitute reconfigurations of society as a result of the evolution of the life sciences.

One implication of ANT is that the dynamics of sciences such as genomics cannot be appropriated by focusing only on either the scientific concepts such as DNA and the genome or the ‘context’ in which they are used, for this would again result in a reduction of scientific and technological artefacts to either natural, social, or discursive categories. ANT-based models of the dynamics of science overcome this reduction by showing how such conceptual and contextual elements result from the flow of human actors and nonhuman participants through actor-networks developing over time. For capturing the dynamics of sciences such as genomics, thus, at least five loops have to be taken into account simultaneously (Figure 1).

{Figure 1 about here}

The first loop, also known as the ‘mobilization of the world’ (Latour, 1999, p. 99), refers to all those processes mediated by tools, objects, and artefacts, that is, ‘all the means by which nonhumans are progressively loaded into the discourse’ (Latour, 1999, p. 99). It is the logistics of science, dealing with surveys, instruments and equipment by which the world is converted into inferences, starting at sites and aiming at transportation towards laboratories where the world is assembled and contained into increasingly encompassing collections and representations. In the case of genomics, this loop refers to the laboratories stuffed with DNA-sequencers, DNA-amplifiers, DNA-chips, and other tools by which scientists transform parts of organisms to pictures and tables that stand for (parts of) ‘genomes’.

The second loop represents how a researcher finds colleagues and is called autonomisation, which 'concerns the way in which a discipline, a profession, a clique, or an 'invisible college' becomes independent and forms its own criteria of evaluation and relevance' (Latour, 1999, p. 101-102). This loop thus includes the institutionalizing of scientific enterprises and the inherent formation of what are called 'epistemic cultures' (Knorr-Cetina, 1999). One important sign of autonomisation of a discipline is the emergence of scientific journals entirely devoted to the scientific discipline. In genomics, for instance, this is already the case since 1987 when the first volume of the scientific journal called *Genomics* was issued.

The third loop—alliances—shows that no scientific enterprise is completely autonomous, but is dependent from allies. In case of genomics, it concerns institutions such as medicine, the judicial apparatus, insurance companies, the industry, and the government, who each have an interest in its knowledge and products.

The fourth loop is public representation, the process by which novel objects of science become massively socialized and part of the discourse in the public domain. For instance, whereas the word 'DNA' was once a particular name heard mainly in laboratories to denote a particular chemical substance in the cell nucleus, it is today part of daily speech. This also counts for concepts such as 'DNA fingerprinting', 'DNA chip', and 'genome'—concepts that were once only used by scientists in sciences like genomics but which can be found today in the science pages of common newspapers. Indeed, the need for incorporating genomics in science curricula at high school is also part of this loop representing public representation.

Finally, the circle in the centre, the fifth loop, refers to the conceptual elements of a science. In case of genomics, we speak of the concept of 'genome' as the most pivotal conceptual element. Such conceptual elements are envisioned as a series of links and knots that tightly keep the other loops together rather than the 'conceptual *content*'. This is not to say that these elements are less 'hard' than scientific concepts, but 'this hardness is not that of a pit inside soft flesh of a peach. It is that of a very tight knot at the centre of a net. It is hard because it has to hold so many heterogeneous resources together' (Latour, 1999, p. 106).

Collectively, the five loops are what Latour calls metaphorically the science's *blood flow* wherein the fifth loop functions as the heart—it keeps the other loops running. If there were no fifth loop, the other four would die off at once. As such, this sociocultural perspective on the concepts of science implies a topology that is different from those common in the cognitive sciences: 'The content of science is not something contained; it is itself a container' (Latour, 1999, p. 108). That is, from a cognitive perspective the 'contents' of genomics—that is, concepts such as 'genome' and 'DNA'—would be commonly understood as something that students, as an outcome of education, should ultimately *contain* 'in their minds'. However, a strong focus on the conceptual contents of science easily leads to a static, canonical model of science misappropriating its dynamics (Figure 2). If the links and knots (left) are excised from the other four loops it will be transformed in a core (middle). The now disconnected four other loops will form a sort of 'context' of no relevance for defining the inner core. The result is a static conceptual content encompassed by an opaque 'context' in which the loops cannot be distinguished anymore (right). Thus, to avoid misappropriating the dynamics of science, we take the perspective of ANT. This sociocultural perspective allows a topology that appropriates the dynamic, hybrid and contextualized nature of concepts such as 'genome' and 'DNA' inherent to their nature of holding together (contain, stand for) an entire scientific discipline. As such, we take the contents of genomics, not as something to be contained by students but as containers, that is, as links and knots that hold together dynamic flows such as those inherent to the instruments, autonomisation, alliances, and public representation. Note that according to such a perspective the traditional distinction between content in terms of either factual knowledge and procedural knowledge is no longer relevant. Procedural knowledge is inherent to the content in the sense that the latter mobilizes the use of instruments by actors.

{Figure 2 about here}

## *Definitions of Scientific Literacy and the Dynamics of Science*

Since its emergence in the 1950s, the concept of scientific literacy has always been hard to define. Ongoing efforts to do so resulted in many different definitions of scientific literacy that are often not mutually exclusive. In review studies, some authors distinguish between two trends in those definitions that refer to scientific literacy in terms of either the content of science or its sociocultural context (e.g., Roberts, 2007). However, such a distinction would introduce a dichotomy in notions of knowledge discursively associated with definitions of scientific literacy *a priori*, which, according to the perspective of ANT, easily leads to misappropriating the dynamics of science. Thus, to avoid such reductions beforehand, I focus on the different notions of knowledge discursively associated with definitions of scientific literacy. In doing so, three trends can be distinguished that are each still present today. In what follows, each of these trends will be briefly reviewed to illustrate in what respect definitions of scientific literacy appropriate the dynamics of science.

### *Scientific Literacy as Cognitive Objectives*

Since its introduction in the North American academic debate on curriculum reform, the concept of scientific literacy was associated with the objectives of science education (e.g., Hurd, 1958; McCurdy, 1958; Rockefeller Brothers Fund, 1958). At the time, there was much confusion about the purpose of science education in the US. World

War II had brought concerns about catastrophic uses of science, such as the atomic bomb. In addition, the launch of the Sputnik showing the Russians' scientific leap forward raised awareness of the role of science in safeguarding national security. As a result, the objective of science education was conceptualised as more than only contributing to an increased output of highly specialized scientists and engineers. In addition, every educated person had to be 'literate in science' (Rockefeller Brothers Fund, 1958, p. 369) because society required citizens that could appreciate and understand what scientists and engineers were doing. Thus, rather than a collective property of society, scientific literacy came to be understood as a characteristic of individual citizens.

In education, scientific literacy came to be articulated as the attribution of scientific 'content' to the student. Thus, this content was commonly defined in terms of *cognitive objectives*, which by and large framed how such scientific 'content' was theorized (e.g., Agin, 1974; Miller, 1983; Pella, 1976; Pella, O'Hearn, & Gale, 1966). For instance, in order to bring coherence in the many different definitions of scientific literacy, one research project attempted to review the literature in terms of Bloom's Taxonomy of Educational Objectives (e.g., Gabel, 1976). Such attempts were encouraged by an influential report, *A Nation at Risk: The Imperative for Educational Reform* (NCEE, 1983), which advocated strong standards-based education in response to disappointingly low test scores of American youth in math and science. The resulting academic achievements turned out to be highly influential. Following three decades on the birth of the concept, definitions of scientific literacy were almost exclusively in terms of attributing particular scientific content to the individual. And even up to today, major curriculum reform documents such as *Benchmarks for Science Literacy* (AAAS, 1993) and the *National Science Education Standards* (NRC, 1996), and their seminal predecessor, *Science for All Americans* (Rutherford & Ahlgren, 1989), treat scientific literacy by and large in terms of scientific content students are supposed to learn and know.

Regarding the appropriation of the dynamics of sciences such as genomics, it is important to distinguish between scientific literacy as a concept referring to the aims of science education in terms of scientific content and scientific literacy in terms of knowing and learning. For instance, in a recent review, scientific literacy is defined in terms of nine distinct aims of science teaching, of which one reads as follows: ‘Science classes should give students the *knowledge* and *skills* that are useful in the world of work and that will enhance their long term employment prospects in a world where science and technology play such a large role’ (DeBoer, 2000, p. 592, emphasis added). Aims like these can be found repeatedly in major curriculum reform documents and in this respect the review is certainly to the point. Indeed, as illustrated with loop 3 of Figure 1, sciences such as genomics always co-evolve dynamically with professions in medicine, industry, and so on. However, aims like the above do not make clear what exactly will change when a science class gives students ‘knowledge’ and ‘skills’. In other words, such definitions do not articulate the nature of the cognitive entity that is, for instance, useful in the world of work and that will enhance students’ employment prospects in scientifically and technologically sophisticated world in which sciences such as genomics co-evolve dynamically with professions. Accordingly, such definitions blur how scientific literacy appropriates the dynamics of science, *despite the explicit referents to the latter that are made*. That is, although the previously mentioned definition of scientific literacy refers to the alliance between the sciences and the world of work, it does not make clear how this aim exactly contributes to understanding this aspect of the dynamics of science. Indeed, having the knowledge and skills that are useful in the world of work does not guarantee any knowledge of how the practice of professionals plays into the dynamics of sciences such as genomics. Evidentially, this definition of scientific literacy includes a focus on science content that overshadows its nature as the knots and links pertaining to the dynamics of science (see Figure 2). Hence, in order to appropriate the dynamics of sciences such as genomics, scientific literacy should be defined in terms of what it means to know and to learn rather than only in terms of the aims and outcomes of this learning and knowing.

### *Scientific Literacy as Individually Constructed Knowledge*

During the 1980s, science educators started to explicate in more detail what the concept of scientific literacy meant in terms of knowing and learning. This had to do with the emergence of constructivism as a dominant framework in science education research. As a result, researchers attempted to illustrate how knowledge is *constructed* in the process leading to increased scientific literacy. For instance, *Science for All Americans* explicitly refers to this process: ‘People have to construct their own meaning regardless of how clearly teachers or books tell them things. Mostly, a person does this by connecting new information and concepts to what he or she already believes’ (Rutherford & Ahlgren, 1989, p. 198). Nonetheless, definitions of scientific literacy in terms of the aims of science education emphasizing scientific content remained dominant. Therefore, rather individual and Piagetian versions of constructivism were applied to define scientific literacy in terms of what it meant to know. The resulting curriculum reform documents focused rather on knowledge as an individual cognitive entity, which ‘at least as exemplified in science education research, tend to assume that the teaching and learning process is directed toward producing students who, through their own activity, come to share established scientific knowledge’ (Eisenhart, Finkel, & Marion, 1996, p. 278). Accordingly, a balance was maintained between established but implicit conceptions of knowledge in terms of scientific content and then-popular and explicitly adopted conceptions of learning and knowing. Most major curriculum reform from documents the late 1980s and the 1990s feature this balance (e.g., AAAS, 1993, NRC, 1996, Rutherford & Ahlgren, 1989). Scientific literacy was thus commonly defined in terms of individually constructed but more or less static scientific content ‘possessed’ by individuals. The 'static' nature of this scientific content results from Piagetian readings of constructivism in particular, which focus on established scientific knowledge rather than knowledge in terms that are characteristic for human cognition. According to current, so-called 'second generation' cognitive theories, human cognition is comprised of fuzzy and contextual concepts, thought as perceptually rather than formally grounded, and largely metaphorical and narrative (Klein, 2006). Therefore, Piagetian readings of constructivism are considered as less viable for explaining how individuals construct knowledge and they cannot be considered exemplary for the current state of the art of constructivism anymore.

Regarding the appropriation of the dynamics of science, the individual constructivist perspective is problematic in at least two ways. The first problem is that scientific literacy, despite being the result of a construction, is still defined as scientific content that can be contained by individuals. Inherently, this perspective on knowledge still overshadows the conceptual content of science as knots and ties, that is, as containers of alliances, instruments, colleagues, and other such elements that collectively make up the dynamics of a science such as genomics (see Figure 1). Therefore, such a perspective on scientific literacy contributes to a context-concept dichotomy that is at odds with appropriation of the dynamics of science (see Figure 2).

The second problem is that scientific literacy is not only defined as scientific content that can be contained by individuals, but also refers to scientific content as established and hence rather static scientific knowledge. This emphasis on scientific knowledge as a static and established entity also overshadows the content of science as containers of other flows that make up the dynamics of science such as genomics (see Figure 1 and 2). More so, such an emphasis leads to the conclusion that scientific literacy simply cannot be present among non-scientists, for it can be argued that established scientific knowledge is too complex to be mastered by everyone, *just because it is scientific knowledge* (Shamos, 1995). The desired level of scientific literacy required for mastering this knowledge, also known as ‘true scientific literacy’, is such that ‘the individual actually knows something about the overall scientific enterprise’ (p. 89). Accordingly, this level is inaccessible to the majority of the citizenry. Scientific literacy defined in terms of scientific content is thus at odds with the idea of scientific literacy as prerequisite for *all* citizens in a scientifically sophisticated society. These paradoxical consequences of defining scientific literacy in terms of individual and static conceptions of knowledge have led science educators to rethink the concept.

### *Scientific Literacy as an Emergent Feature of Collective Human Activity*

During the 1990s, several (groups of) researchers began to explicitly rethink conceptions of knowledge that are discursively articulated with scientific literacy. This rethinking focused on declarative scientific knowledge (concepts, formulae, etc.) as the core of science curricula that aim for scientific literacy and which characterizes standards-based curriculum reform documents. This rethinking became particularly prevalent when focusing on the broad aim of scientific literacy of ‘producing citizens who can use science responsibly and including more people in science’ (Eisenhart et al., 1996, p. 269). In general, it was doubted whether the individual ‘acquisition’ of a discrete and testable body of knowledge of scientific concepts and methods leads to an increased and more diverse citizenry that uses science responsibly in their daily lives or profession..

One argument to doubt the assumption that individual ‘acquisition’ of scientific to be congruent with the broad aim of scientific literacy has to do with the relevance of knowledge learned in schools. Specifically, the specialized knowledge that is summed in curriculum reform documents is both inaccessible by direct experience and irrelevant in the majority of people’s daily lives (Roth & Barton, 2004). The knowledge taught in school science is all too often a ‘beyond dispute’ variety, which is a very poor preparation for science as it is encountered in daily life (Durant, 1993). There is little evidence that knowing school-like facts and basic skills contribute anything to competent functioning in the everyday world. On the contrary, ample evidence from studies on the use of mathematics in daily life suggests that there is no correlation between what is taught in schools and levels of performance in everyday mathematical tasks (Lave, 1988; Scribner, 1986).

In other words, there is no reason to believe that the individual ‘acquisition’ of scientific content will lead to an increased citizenry that will use science responsibly in their daily lives or profession. In this regard, science educators have repeatedly argued for rethinking conceptions of knowledge discursively associated with scientific literacy. Such calls argue for the lens of second-generation cognitive theories as the groundwork required for defining scientific literacy in a way that would be congruent with the broad aim of scientific literacy (e.g., Klein, 2006). Understanding controversial and complex socio-environmental scientific issues such as inherent to the dynamics of science thus requires, at a minimal level, complexity of content, context, and method in the classroom (Colucci-Gray, Camino, Barbiero, & Gray, 2006). Recent elaborations of such notions of complexity of content and context as a prerequisite to foster scientific literacy attempt to bring scientific discourse and controversy into schools (e.g., Duschl, Schweingruber & Shouse, 2007). Ideally, one of the outcomes of bringing science into schools accordingly is ‘to forge a link between scientific experimentation in schools and emerging ideas of scientific literacy’ (Gott & Duggan, 2007, p. 271).

Bringing science into school *reproductively*, however, is not enough to foster scientific literacy. Indeed, studies of speech practices inside and outside of schools have shown that academic science discourse privileged in school science may actually discourage socially helpful and responsible uses of science in situations students may encounter in daily life and future professions (Eisenhart et al., 1996). This is due to the privileging of particular voices that is inherent to conventions of scientific discourse (e.g., Calabrese Barton & Osborne, 2001; Eisenhart & Finkel, 1998). These studies are grounded in critical perspectives (e.g., feminism, postcolonialism) that articulate relationships that exist between knowledge and the relations of power that privilege the particular voices and hands that articulate, construct, and thus constitute such knowledge (cf. Foucault, 1979). Framing scientific literacy in terms of scientific concepts and methods thus facilitates speech genres and modes of action that are constitutive of and preferred by conventional science. Accordingly, the privileged way of knowing and doing is the common scientists' way, which largely exhibits white middle-class and male epistemologies. Minorities and women are therefore often discouraged from doing science or from moving into science careers (Roth & Barton, 2004).

The issue of privileging specific discourses in school science is more or less maintained by the previously mentioned notions of knowledge as an individual cognitive entity that are rooted in particular readings of constructivism. Indeed, such frameworks fail to emphasize the connection of 'content' with the wider activities that have to do with school science but which go beyond the individual such as schooling, science, and work. To overcome this limitation, therefore, scientific literacy was rethought from frameworks that appropriate such wider activities. This is not to say that scientific literacy is to be thought in terms of such wider activities regardless of scientific knowledge. Rather, such rethinking is in line with the perspective of ANT in the sense that scientific content and the wider activities in which it manifests are thought relational. Both ANT and this rethinking of scientific literacy employ a unit of analysis in which content and context are no longer thought independently from each other. In both approaches, a focus on either the context or the content— as is the case in the right-hand model of Figure 2)—is avoided. Thus, what 'constitutes 'knowledge' at a given moment or across a range of situations is a matter of analysis, which has to take account of the motivations, interests, relations of power, goals and contingencies that shape the activity' (Roth 2003, p. 17). Hence the idea emerged that scientific literacy can be perceived as an emergent feature of collective human activity.

Human activity is composed of ‘many, often dissimilar and contradictory elements, lives, experiences, and voices and discontinuous, fractured and non-linear relationships between these elements, lives, experiences, and voices’ (Roth 2003, pp. 17-18). What ultimately counts as ‘scientific literacy’ can thus only be understood by analysis of these systems, that is, by examining the manifold and interdependent means (speech, texts, tools, actions) by which knowledge is produced by and hence distributed over and situated in collective human activity. ‘Emergent’, then, refers to the interdependent relationship in the evolving setting that at certain points exhibits specific characteristics such as scientific literacy.

Thought from the perspective of collective human activity, knowledge is collective and distributed over the activity. For instance, in one case study of school science, students were asked by a local organization to restore a pond located on their property that was in poor health, stagnant and smelly (Eisenhart et al. 1996). In response, they developed a restoration plan and this work required the students to situate their tasks in the local community, establish relationships with experts and community members beyond the school, and developed ways of talking and writing that were useful and persuasive in a real-world setting. Here, scientific literacy emerged as the students collectively cultivated understandings of scientific concepts and ideas that were both locally useful and technically sophisticated.

In another case study of science in a rural community citizens interacted with scientists during an environment-oriented open-house event centred around a dispute on local water resources (e.g., Roth & Lee 2002). This case study showed that collectively, much more advanced forms of scientific literacy are produced than any individual (including scientists) could produce. For instance, the citizens questioned a scientist about the methodology he used, which turned out to fall short considering the problem at hand. Here, scientific literacy cannot be explained as individual, discrete and testable knowledge. In these latter terms, both citizens’ questioning and scientists’ inadequate response would be understood as a lack of understanding of appropriate scientific methods. As collective activity, however, scientific literacy can then be understood as an emergent feature of a transaction between scientists and citizens developing over time. In this case, the scientist is not longer privileged as the one who defines what the scientifically literate citizen 'needs' here. Nor is knowledge something that is 'used' by citizens in a scientifically sophisticated society. Rather, citizens and scientists collectively produce the scientific knowledge that is constitutive for the emerging scientific literacy, which, in turn, contributes to a scientifically sophisticated society. As shown in another study, such forms of scientific literacy can also emerge in the context of school science as transactions between students, scientists, and the community developing over time (Author & Colleague, 2007).

Definitions of scientific literacy that frame knowledge as collective human activity, appropriate the dynamics of sciences such as genomics in several respects. According to this frame, scientific content is not defined as something that is contained by individuals, but as tools in human activity. For tools are dialectically linked with the wider activity in which they are used, they can be thought as being inextricably bound up with and hence keeping together other aspects of activity, such as the human subjects whose actions are mediated by these tools, the communities in which they are used, and the specific rules that are associated with tool use. Hence, scientific content relationally contains the other elements of human activity rather than being fully contained by the individual human subject that is also part of this practice. In this way, scientific content is thought as being more or less similarly to the knots and links that make up in part the dynamics of sciences such as genomics (Figure 1). More so, when scientific content is understood dialectically as knots and links that keep together the other aspects of collective human activity, they can only be thought as relational with the context it shapes and is shaped by. Indeed, perceived from a perspective of knowledge as collective human activity, scientific content is *part of* rather than *different from* this context. When scientific literacy is thought as an emergent feature of collective human activity it cannot overshadow itself, that is, the knots and ties that keep together alliances, instruments, colleagues, and other such elements that collectively make up the dynamics of science (Figure 2).

### *Collective Activity and Students' Agency in Genomics Education*

Curricular reform towards scientific literacy as an emergent feature of collective activity is a difficult task. This is so because the science curricula resulting from such reform would be very different compared to common practice in current school science. The key issue here is the extent to which students engage meaningfully and develop competent participation in scientific activities—an issue with which science education research struggles for decades. In the two activities from the domain of ecology that were illustrated previously, students' actions are meaningful not so much because they *resemble* scientific practice but because they *constitute* scientific practice. Currently, schooling in science does not provide students with many opportunities to engage meaningfully and develop competent participation in activities that bear considerable resemblance with the activities that produce scientific knowledge. This is so because schooling activities are supposed to unfold in particular predetermined ways, leading students in 'mastering' specific scientific 'content' or 'procedures'. For instance, schooling in genomics is often preoccupied with the 'groundwork' that has to be laid in order to understand issues in genomics, that is, the content denoted by concepts such as 'cells', 'chromosomes', and 'genes' (e.g., Kirkpatrick, Orvis & Pittendrigh, 2002; Corn, Pittendrigh & Orvis, 2004). In other instances, there is a focus on 'scientific inquiry' but one that reduces the scientific activities in genomics to 'knowledge' and 'technical skills' (e.g., Chen et al., 2005; Hanauer et al., 2006). Accordingly, science curricula often define scientific literacy in terms of such content that is supposed to be contained by individual students rather than a container that holds together the dynamic flows of science (Figure 1). More so, in terms of collective human activity, students are often withheld from the agency by which they can exert the power over elements that collectively determine how the activity will unfold. For instance, in school science, it is not common that students are allowed to participate in setting the goals and objects of their activities, choose tools, determine a division of labour, or participate in the constructing of the going rules. The result is that rather than collectively becoming scientific literate, students are becoming literate in meeting the aims of the schooling activity, that is, in getting high grades by reproducing the scientific 'knowledge' and 'skills' on tests. Students engage thus in a form of learning which is called *defensive learning*—a form of learning that has the function to avoid punishment (Holzkamp, 1993).

To engage meaningfully and hence develop competent participation in knowledge-producing activities in science, students should be given the agency to co-determine the way in which such activities unfold over time. In a science education envisioned from this perspective, the emerging scientific literacy appropriates the dynamics of science such as genomics. Indeed, agency allows students to participate in setting the goals and objects of their activities, choose tools, determine the division of labour, or construct the going rules. In other words, it allows students to develop competent participation in keeping these activities running and to find allies, to design instruments, to mobilize the world, and so on. More so, agency allows students to develop and hence understand how particular elements of knowledge-producing activities in science, such as rules, objects, and tools, are used as knots and links in holding together the dynamic flows of these activities. In short, agency over knowledge-producing activities in science allows students to experience collectively how 'methods', 'instruments', and 'concepts' emerge as knots and links containing the dynamic flows of sciences such as genomics. Indeed, recent research on authentic practices in school science revealed that the problem of fostering scientific literacy does not lie with the level of agreement between school science and laboratory science but with the levels of control, authority, mastery, and authorship that students are enabled to exercise (Colleagues & Author, 2008).

## *Implications for Genomics Education*

The vision on teaching genomics for scientific literacy outlined so far has substantial implications for curricular reform. For instance, genomics education according to more authentic ways requires a repertoire of teachers that differs substantially from what is common in current practice. In current practice, teachers are familiar with schooling activities that are supposed to unfold in particular predetermined ways, leading students in ‘mastering’ specific scientific ‘content’ or ‘procedures’. In contrast, genomics education that addresses the dynamics of science is open-ended, and leads to certain links and knots between the dynamic flows of genomics that cannot be known beforehand. And just because of this open-ended nature of curricula that address the dynamics of genomics, it is inherently impossible to provide a concrete lesson plan that neatly covers all the flows that represent the dynamics of a rapidly developing science in its entirety. However, this does not mean that the implications for genomics education are too invasive to be implied in current practice. Rather, bridging this vision and current practice is a matter of several subsequent steps. Such steps start with the given that students’ agency rather than resemblance with current scientific activities is the key issue. Hence students in genomics education do not necessarily need to do the same things that genomics scientists do in their laboratories. Indeed, even experiences in highly sophisticated DNA laboratory settings may deprive students of science authenticity while less sophisticated classroom-based science may provide opportunities for doing science in an authentic manner, that is, with high levels of control over the learning environment, authority, master, and authorship. Quintessential here is not finding problems that bear some correspondence to school problems or activities in scientific laboratories—a pitfall frequently employed by science educators, but in finding authentic problems that are truly problematic to students (Lave, 1992).

Thus, from the perspective of agency and authenticity, modest steps can already be taken in curricular reform towards a school science in which genomics is taught from the perspective of scientific literacy as an emergent feature of collective activity. One such step could be to make students aware that they already engage in some way in the enterprise of genomics. Indeed, students participate in a society that is, in part, continuously in the making by the advances of sciences such as genomics. Particularly, in regard to the flows that deal with public representation and alliances, educational activities are within reach or have already been developed that may help students to become aware of this aspect of their participation in society.

In genomics, the flow of public representation is currently rapidly increasing. This increase is by and large due to the impact of genomics on issues pertaining to health and medicine. The discipline of health behaviour and health education (HBHE) is currently claiming a leadership role in the integration of genomic advances to improve the public's health (Kardia & Wang, 2005). Thus, HBHE-activities such as decision-making processes, genetic risk communication, and informed consent processes are rapidly becoming more important in society. This not only counts for health practitioners who are engaging in such HBHE-activities professionally but also for children who, as future citizens, will increasingly be confronted with these activities as patients or in mass prevention programs. Thus, what children learn in school about genomics may have significant implications for broader public education measures in genetic literacy, genetic counselling, public health practices, and even routine health care (Lanie et al., 2004). Hence all these activities have direct practice implications for genetic education (Wang, Gonzalez, & Merajver, 2004).

At a minimal level, then, students should become aware of, take part in, or be prepared for such HBHE-activities pertaining to genomics. Such an education provides opportunities to take another step towards scientific literacy and the inherent appropriation of the dynamics of science. By taking the agency of the student central, the ‘content’ in such an education should be understood as a link that mobilizes public representation in regard to the decision making with which students are confronted with in HBHE-activities. For instance, research on HBHE-activities already reports an onslaught of genomic terminology and technology on health professionals and the general public (Wang, Bowen & Kardia, 2005). Thus, science curricula can be setup such that students investigate examples of this onslaught with the aim to understand for what scientific activities this terminology stands, how it affects their decision making, and how the terminology can be altered so that they or their peers will make better informed decisions. In these lessons, students can go one step further and contact genomics researchers who provide support in explaining the terminology involved, thereby linking the ‘content’ of genomics to decisions students are confronted with in HBHE-activities. This step is not so uncommon, given that fruitful partnerships between schools, science teachers, and genomics researchers who provide services to education have already been setup successfully (e.g., Munn, Skinner, Conn, Horsma, & Gregory, 1999). As such, students can engage in the scientific enterprise actively while keeping their agency as student-practitioners. In turn, setting up such networks implies a new role for teachers—a role that can be understood as ‘knowledge brokers’ between students on the one hand and genomics researchers on the other hand. In addition, in prior research on authentic scientific practices in schools, teachers had the roles of guides that introduced particular instruments or procedures to students in response to their needs in authentic practices (Author & Colleague, 2007). Likewise, in response to students’ needs, teachers can introduce students to common instruments in genomics research. In this way, the flow of instruments can be connected to the flow of public representation by which students learn how such flows of genomics mobilize each other and which ‘content’ plays a role in such mobilizations. Accordingly, students are more likely to understand ‘content’ as links and knots that mobilize the other flows in the dynamics of science as represented in Figure 1.

Simultaneously, students’ awareness of the flow of alliances that exist between genomics and other institutions in society can also be addressed through collective activity. The fact that HBHE-activities are becoming increasingly important in society indicates that the health care enterprise is one of the major allies of the science of genomics. Other major allies are enterprises such as the biotechnology and pharmacy industry and the government. Each of these stakeholders is allied to genomics research for particular purposes and hence each alley affects the other flows of genomics research in particular ways. Hence alliances between genomics research and other institutions differ with respect to serving the needs of students, their families and their community. In lessons on genomics for scientific literacy, students can conduct investigations in which they explore in what particular ways alliances between stakeholders and genomics research serve which personal, communal, and social needs. In such lessons, students can participate in networks of science teachers, genomics researchers, and business partners which have already been proven successful in genomics education (Munn et al., 1999). However, these networks should provide support for students in a way that allows them to keep control over their investigations and the instruments and methods they use, therewith preserving students’ agency as well.

One may argue that the perspective on genomics education employed here in some way tends to turn science education into a form of social studies. This is true insofar as these studies are limited to the social studies of science in particular. Indeed, in this sense, science education might benefit from framing it as a particular practice-oriented social study of science. Indeed, it has been argued repeatedly that learning about the nature of science should be an integral part of a science education that contributes to the development of scientific literacy (Laugksch, 2000). Accordingly, we should limit science education to social activities that can be considered scientific in some way. A clear description of what can be considered scientific or not in such cases is still a quest of the philosophy of science. In this sense we are theoretically limited and such a treatise would clearly go beyond the scope of this journal.

## *Implications for Further Research*

In the foregoing I have illustrated how, in case of genomics, the dynamics of science can be addressed in curricular reform for scientific literacy. However, much research is required to develop effective genomics curricula that nurture scientific literacy accordingly. The major problem for researchers in this field is to find ways by which the ‘content’ of genomics can truly come to serve as links and knots by which students, at a minimal level, learn how to mobilize the other flows of science. For instance, in case of genomics, it is tempting to setup laboratories where students do basically the same things as scientists do in their laboratories so that they learn some basics of the instruments involved (e.g., Chen et al., 2005; Hanauer et al., 2006). However, from a perspective that captures the dynamics of a science such as genomics, laboratory activities to which the use of instruments is central, can be considered as only one of the loops that keep alive the work of scientists (Figure 1). Without mobilizing the other flows and forging links and knots between the flows, the doing of such work does not address the dynamics of genomics and the full potential of increasing scientific literacy will probably not be harvested. In contrast, when scientific literacy is thought as an emergent feature of collective human activity, such activities should not only resemble the use of tools in the laboratory but also address the mobilization of the other flows of genomics such as public representation and alliances. Therefore, educators are in need of activities that position such ‘DNA-labs’ in a wider collective human activities that foster scientific literacy in genomics and in which students can participate (e.g., Waarlo et al., 2009a, b). The key issue for further research is thus finding collective activities that grant agency to students in regard to mobilizing the flows of the dynamics of genomics and hence to allow them further steps toward participation in the science of genomics.

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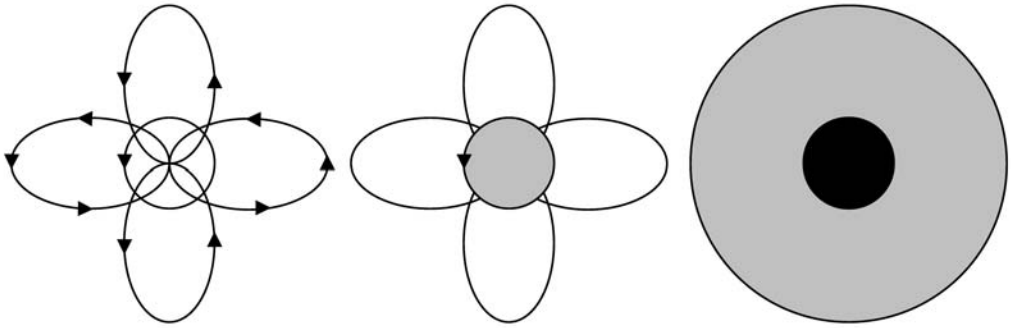

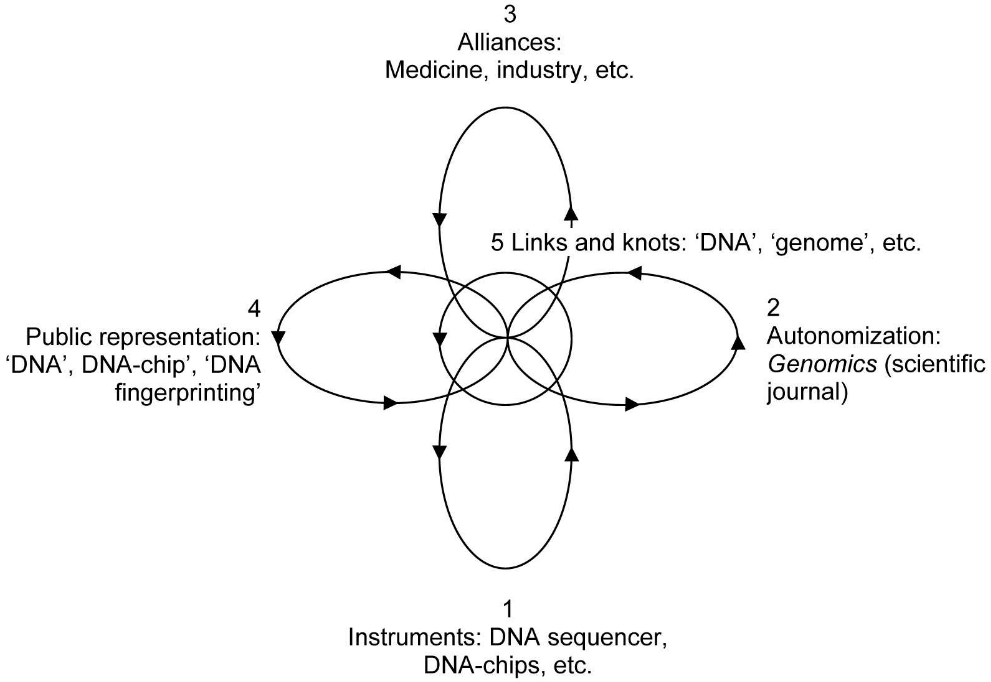

Figure 1 ANT-based model of the dynamics of science (after Latour, 1999)
135x93mm (300 x 300 DPI)

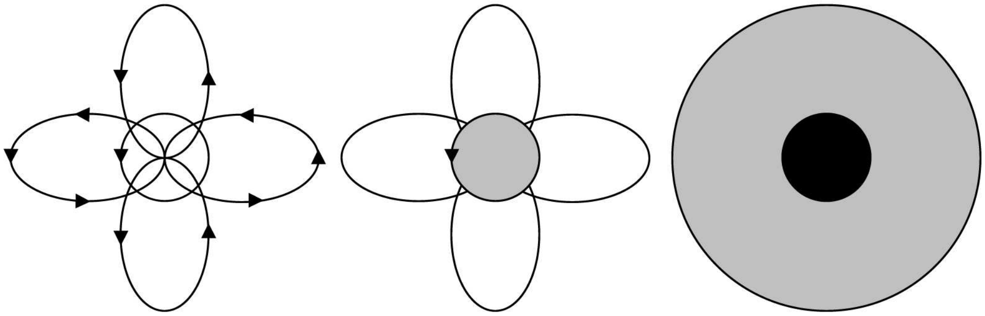

Figure 2 Decreasing appropriations of the dynamics of science (after Latour, 1999)
135x44mm (300 x 300 DPI)