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# Interactions of Economics of Science and Science Education: Investigating the Implications for Science Teaching and Learning

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**Abstract** In recent years, there has been upsurge of interest in the applications of interdisciplinary perspectives on science in science education. Within this framework, the implications of the so-called "economics of science" is virtually an uncharted territory. In this paper, we trace a set of arguments that provide a dialectic engagement with two conflicting agendas: (a) the broadening of science education to include the contextual positioning of science including economical dimensions of science, and (b) the guarding of the proliferation and reinforcement of those aspects of economics of science such as commodification of scientific knowledge that embraces inequity and restricted access to the products of the scientific enterprise. Our aim is broadly to engage, as science education researchers, in the debates in economics of science so as to investigate the reciprocal interactions that might exist with science education. In so doing, we draw out some recommendations whereby the goals of science education might provide as much input into the intellectual debates within philosophy of science on issues related to the commercialisation and commodification of scientific knowledge. We explore some implications of commodification of science in the context of modelling and argumentation in science education.

## 1 Introduction

In recent years, there has been upsurge of interest in the applications of interdisciplinary perspectives on science in science education. Here by "science education" we refer to the academic discipline that aims to produce theoretical and empirical knowledge on various

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educational constructs such as teaching, learning and curriculum in science. "Science Studies", the interdisciplinary set of investigations on the nature of science, are contributing to the aim of informing science education of the foundational perspectives from a range of disciplines, including cognitive science, philosophy of science, artificial intelligence and sociology of science (Duschl et al. 2006). Within this interdisciplinary research framework, the implications of the so-called "economics of science" are virtually an uncharted territory in science education. Conceptually related but historically distinct and different lines of research, namely "Socio-Scientific Issues" (SSI) (e.g. Sadler 2011; Zeidler et al. 2005), "Science-Technology-Society-Environment" (STSE) (e.g. Aikenhead 2003; Gaskell 1982; Yager 1996), "History, Philosophy and Sociology of Science" (HPS) (e.g. Matthews 1994), and "Nature of Science" (NOS) (e.g. Lederman et al. 2002) have argued for situating science in its historical, socio-political, economic and cultural contexts for educational purposes. However the reference to economics in these research areas has been rather broad with practically no theoretical import from the formal discipline of "economics of science".

There are at least two key rationales for interrogating the intersection of economics of science and science education. The first concerns the grounding of knowledge in science education in relevant bodies of knowledge that concerns the characterisation of science itself. Given the focus on 'science' in "science education", it is entirely appropriate to investigate what (if any) economic features of science should be infused in science education, both in terms of theoretical framing of science but also in terms of the practical implications for science teaching and learning. The second rationale is related to the potential reverse relationship of the contributions of science education research to perspectives on economics of science. Given that the establishment and the maintenance of the scientific enterprise rely on the production of scientists through the education system, it is conceivable that science education knowledge can and should inform arguments in economics of science as well.

An implicit goal underlying the inclusion of economics perspectives in science education is the notion that scientists and the public alike should possess scientific literacy. Here 'literacy' is not meant in a generic sense. Rather, "scientific literacy for all" is a theme that has been advocated in science education research (e.g. Brown et al. 2005; Gott and Roberts 2004; Holbrook and Rannikmae 2009; Laugksch 2000; Lemke 2004; Norris and Phillips 2003) and international policy initiatives (National Research Council 1996; OECD 2006) quite explicitly and strongly in recent years. Numerous curricula in the world have already embraced and promote the teaching and learning of "scientific literacy" in schooling. For instance, Erduran and Wong (2013) have conducted a comparative study of science curricula in England and Hong Kong for their coverage of themes related to scientific literacy. Roberts (2007) distinguished two visions of scientific literacy. Vision 1 describes an understanding of the enterprise and epistemology of science and could be considered as what the public should know about the science used by society. Vision I surfaced in 1985 with the beginning of AAAS *Project 2061*. The project's *Benchmarks for Science Literacy* and *Atlas of Science Literacy* have influenced the thinking of educationalists in the USA and worldwide. The notion of "science as economic enterprise" is consistent with Vision 1 scientific literacy. Here the goal for science teaching and learning would entail the articulation of the economics that drive, shape, hinder or enable scientific inquiry. Vision 2 involves understanding the world as a scientist would, i.e. being able to offer explanations and hypotheses about the world. Generating theories and knowledge claims are seen as the key activities of science. This is exemplified in the definition of scientific literacy provided by the National Research Council (1996, p. 22):

> Scientific literacy means that a person can ask, find, or determine answers to questions derived from curiosity about everyday experiences. It means that such a person has the ability to describe, explain, and predict natural phenomena.

Our subsequent discussions will illustrate that the Vision 2 notions of scientific literacy may not be immune from economics either, due to the commercialised nature of some scientific knowledge such as patented genetically modified organisms. We should note that economics of science has an uneasy standing for science education. On the one hand, the enculturation of students to the financial dynamics of the scientific enterprise is a goal that would align science education with goals that are faithful to the very conceptualisation of science in context, encapsulating the Vision 1 scientific literacy. Informing science education with perspectives from economics of science would further be consistent with recent trends on the interdisciplinary characterisations of science in science education. On the other hand, however, the scepticism that surrounds the nature of such financial dynamics including the commodification and commercialisation of scientific knowledge restricting access to knowledge (e.g. Irzik 2010) lends itself to the need for science educators to cast scrutiny to the adaptation of economic arguments in education.

In this paper, we will trace a set of ideas that provide a dialectic engagement with these two conflicting agendas: (a) the broadening of science education to include the contextual positioning of science, namely the economic dimensions of science, thereby contributing to the research basis of science education as well as the pragmatic scientific literacy agenda, and (b) the guarding of the proliferation and reinforcement of those aspects of economics of science such as commodification of scientific knowledge that can promote inequity and restricted access to the products of the scientific enterprise. As science educators, our aim is broadly to engage in the debates in economics of science so as to investigate the potential interactions that might exist with science education. First, we will question the extent to which recent research in science education promoting "science in context" has articulated the economic dimension of science. Here we will illustrate as an example how current work on NOS is underspecified with respect to the characterisation of science. This section will warrant the need to extend the theoretical characterisations of 'science' in science education research. Second, we will trace some selected notions from economics of science and explore their implications for science education. We will focus on the issues of patent rights and the discovery/invention dichotomy and highlight how they can be embedded in science education. Across both instances, our discussion will be mindful of the evidence-base in science education for effective teaching and learning. For instance, we will be cognizant to situate these notions in current science education research such as argumentation (e.g. Erduran and Jiménez-Aleixandre 2008) so as to ensure relevance in positioning in science education and to forge realistic uptake in the community for further inquiry particularly from an empirical approach. Our intention is not to problematise economics concepts including, for instance, how science has been commodified in different ways throughout history. As educators, we leave such agendas to the experts in the field. Rather, we are interested in exploring the potential of existing themes for educational applications. Finally we will take on the idea of market economy and apply it as a metaphor to the case of models and modelling in science education. This application will illustrate a potentially new lens for understanding the dynamics of model use in educational contexts. Interdisciplinary considerations of models have focused on cognitive, philosophical, educational and disciplinary accounts of models (e.g. Erduran and Duschl 2004) but have not related different types of models in terms of how they might be guided by economic influences. We will illustrate how the economics lens can reframe the interpretation and conceptualisation of models and modelling in science education research.

## 2 Economics of Science: A Missing Theoretical Framework in Science Education?

Despite a broadly shared agenda to promote the teaching and learning of science in context, the particular foci of science education research with such agenda (i.e. SSI, STSE, HPS, NOS) differ in their theoretical backgrounds, aspirations and indeed how they envisage science itself. For instance, in contrasting the STSE movement and the domain of SSI education, some authors have argued, "STSE typically practiced does not seem embedded in a coherent developmental or sociological framework that explicitly considers the psychological and epistemological growth of the child" (Zeidler et al. 2005, p. 357). Ziman, himself a proponent of STSE, for instance, states, "The fundamental purposes of STS education are genuinely and properly diverse and incoherent" (Ziman 1994, p. 22). Similar criticisms exist for the narrow and underspecified characterisations of science in NOS (e.g. Allchin 2011). The typical coverage in reference to economics in science education within SSI would be in relation to an 'issue' that would provide an interesting and motivating context from the perspective of students. An issue-based curriculum would thus be "…intended to produce activists: people who will fight for what is right, good and just; people who will work to re-fashion society along more socially-just lines; people who will work vigorously in the best interests of the biosphere." (Hodson 2003, p. 645).

It is beyond the scope of this paper to review and assess the theoretical coherence represented and presented in each of these areas of science education research. We will focus on one aspect, NOS, to illustrate how the articulation of economics of science has been virtually inexistent in the conceptualization of scientific knowledge. In so doing, we aim to illustrate what contributions the theoretical insights on economics of science can make to science education. Within science education research literature, NOS has become a widely covered area, as evidenced, for instance by Chang et al. (2010) who traced literature between 1990 and 2007, finding an emphasis on NOS in science education. Studies focusing on recent trends in science education research (e.g. Lee et al. 2009) illustrate that NOS continues to have prominence, and that even though "Culture, Social and Gender" issues have received increasing attention in recent years, the economic analyses of science do not centre in the current landscape of science education research. Of course one could also argue that the conventional depictions of NOS in terms of its cultural and social dimensions are inclusive of economics perspectives. However an examination of some key sources on science education research, for instance through review articles (e.g. Lee et al. 2009), research handbooks (e.g. Abell and Lederman 2007) and critiques of science education research (e.g. Jenkins 2000) does not yield any explicit reference to scholarly work on economics of science as a discipline that can inform NOS.

The predominant definition of the NOS in the empirical studies on teachers' and students' perceptions of science have relied on the characterization of science primarily relative to the cognitive, epistemic and social aspects of science, and have been limited in terms of their conceptualizations of science from broader perspectives (e.g. Allchin 2011) including economics of science. Let us consider the collective set of learning goals for understanding the NOS advanced, explicitly and in a particular sense, by the key proponents of this area of research in science education (Lederman et al. 2002; McComas 1998):

(a) Tentativeness of Scientific Knowledge: Scientific knowledge is both tentative and durable;
(b) Observations and Inferences: Science is based on both observations and inferences. Both observations and inferences are guided by scientists' prior knowledge and perspectives of current science;
(c) Subjectivity and Objectivity in Science: Science aims to be objective and precise, but subjectivity in science is unavoidable;
(d) Creativity and Rationality in Science: Scientific knowledge is created from human imaginations and logical reasoning. This creation is based on observations and inferences of the natural world;
(e) Social and Cultural Embeddedness in Science: Science is part of social and cultural traditions. As a human endeavour, science is influenced by the society and culture in which it is practiced;
(f) Scientific Theories and Laws: Both scientific laws and theories are subject to change. Scientific laws describe generalized relationships, observed or perceived, of natural phenomena under certain conditions;
(g) Scientific Methods: There is no single universal step-by-step scientific method that all scientists follow. Scientists investigate research questions with prior knowledge, perseverance, and creativity.

Even at such propositional characterisation of NOS, it can be argued that the characterisation of science is quite limited. Take for instance, 5 of the 7 statements: (a), (b), (c), (f) and (g) which all imply primarily an epistemological grounding, namely the emphasis on the nature of scientific knowledge and knowledge production procedures. The remaining elements, (c) and (d) are mainly concerned with the cognitive, social and cultural features of science, all rather broad and lacking sufficient detail to differentiate the nuances that, for instance, characterise branches of science. Take, for instance, the arguments for the role of 'classification' in science. From a NOS perspective, classification would be presented as a process that scientists use in order to understand the world. It would potentially be considered a component of (g) above. However, the articulation of 'classification' in philosophy of science (e.g. Bryant 2001) illustrates the complexity in the ways in which different branches of science use classifications. While classification may be prevalent in science, the particular ways in which it is instantiated in different disciplines (e.g. elements in chemistry, species in biology) are nuanced illustrating the domain-specific ways of reasoning. Discipline specific philosophies of science have documented other aspects of scientific knowledge that portray variations in conceptualisation. For example, the concept of 'laws' can have very different meanings in chemistry versus physics (Christie and Christie 2000). If we consider the articulation of the disciplinary variations and specifications of the epistemological (e.g. Scerri and McIntyre 1997) as well as the cultural and social practices (e.g. Knorr-Cetina 1999) of different sciences, the NOS framework above falls short of meaningful grounding of science in authentic (and not overgeneralised) aspects (Erduran 2007). One could indeed query, the nature of *which* science NOS characterisations capture in the first place? Whilst our reference mainly concerns the variation in the sciences from an epistemological perspective (e.g. Scerri and McIntyre 1997), we shall see in subsequent sections that there are also variations in the economics-related practices of science as well. For instance, we will illustrate how the molecular biology and biotechnology fields have been prone in particular ways to the commodification of scientific knowledge.

One of course could argue that NOS needs to be framed for educational purposes in a rather broad sense, given the developmental, curricular and pedagogical constrains that NOS will face in schooling. In other words, whilst the researchers in science education might acknowledge the nuances in the disciplinary variations in science, it may not be practically plausible to import these features for schooling purposes. Considering the abundant literature on children's difficulties with science (e.g. Driver et al. 1996), the argument could go that a broad and underspecified NOS is what is needed in education. The alternative educational imperative is that learning is a situated activity (e.g. Lave and Wegner 1991), and it is only through the nuanced practices of science that learning will be meaningfully situated.

Our aim in this paper is to contribute to the articulation of such specificity that we believe should contextualise 'science', including the context of commercialisation and commodification of scientific knowledge. We will first take on the broad landscape of economics of science to illustrate some issues that might be relevant for consideration in science education. This section will provide some broad ideas on example debates that science educators could benefit from. We will then turn to a more specific coverage of the dichotomy of discovery versus invention. Here we will problematise the introduction of topics in science classroom where learners can make informed decisions about issues such as the invention of genetic material. These two sections will provide examples of how current characterisations of NOS can be extended to embrace more nuanced definitions of context. Our next example will focus on the area of research typically called "models and modelling in science education", a widely studied research area (e.g. Aduriz-Bravo 2013; Gilbert and Boulter 2000) that could be revisited through an economics of science perspective.

## 3 Economics of Science: A Brief Overview of Key Issues

Economists of science have aimed to understand the behaviour of scientists, the distribution of resources and the financial operation of scientific institutions. For example, a question that has been guiding the field is the extent to which science can be understood as a market (Wibble 1998). This section draws from the body of literature has been growing since the systematization of the field of economics of science.[1] Radder (2010) defined commodification as "the pursuit of profit by academic institutions through selling the expertise of their researchers and the results of their inquiries" (p. 4). In this sense, commodification is identified with commercialisation. In an ideal world, where everyone has free access to all scientific knowledge at all times would we be talking about commercialisation of science? The answer of this question is essential to reveal the commercial nature of science. Commercial nature of science is related to the production of scientific knowledge as private property, and the existence and development of science as a market but at the same time creating market barriers to hinder free consumption of scientific knowledge by public and/or rival producers of scientific knowledge. In order to understand the commercial nature of science, we need to make a demand and supply analysis, in which we consider science as a market for scientific knowledge. In the analysis we will first define science and scientific knowledge. Second, we will answer two essential questions: Who supplies and demands scientific knowledge and why?

[1] Diamond (2008), Irzik (2007, 2010), Nowotny et al. (2001), Radder (2010) and Wibble (1998).

Irzik (2007) defines the term ‘science’ as “a system of activity and thought as well as a social institution” (p. 137). By this definition, he refers to “cognitive problems and research agendas, methods, cognitive aims, practices directed toward those aims, ethos and, finally, end products such as knowledge.” (p. 137). Scientific knowledge is produced by using scientific methodology, which is the prime strength of science as a reliable way of knowing and therefore makes scientific knowledge an invaluable product with many positive outcomes. Two main outcomes of science include technology and innovation. The close impact of science on technology is one of the driving forces of economics of science, given technology is itself grounded in notions of productivity, growth, commodities and markets (Diamond 2008). Salomon (1985) argued, “science has ceased to be considered as a system of available knowledge outside the economic circuit” (p. 79). Moreover, consider, for instance, arguments from the economics of science that advances the position that “science has become a commodity whose value is related in economic terms to the laws of supply and demand and in political terms to the objectives and needs of government” (Salomon 1985, p. 80).

Technology and innovation pave the way for new profit opportunities by creating new demand for new products as well as by decreasing the cost of production. Irzik emphasized that as a result of techno-scientific, political, economic, and legal developments the distinction between science and technology becomes less clear. Therefore, scientific knowledge is within the interest of profit seeking commercial firms. Science, technology and innovation are also related to access to power and ways of controlling economic resources as well as societies. A good example is nuclear power. Technology is also related to sustainable economic growth, which is one of the main goals of governments. So, scientific knowledge is also within the interest of governments.

The prime supplier of scientific knowledge in the science market is the scientist. A scientist could be self-motivated to do science, for instance, because of curiosity. But also (s)he is usually a wage earner at a scientific institution such as a research centre and a university. Radder (2010) refers to the hybrid models of science. For instance, a scientific project may possess both the elements of commodified and public-interest science. Today, it is highly unlikely for the suppliers, namely scientists to produce scientific knowledge without funding. The source of funding might vary. The main funders of these scientific institutions and scientists are also usually the states and firms, who demand scientific knowledge due to their previously mentioned interest in having scientific knowledge. For the same reasons, these funders have interest in keeping the newly produced scientific knowledge for their own use and not exposing to public use immediately. This motivation paves the way for commercial nature of science and creating market barriers. Irzik (2007) emphasizes that commodification of scientific knowledge should be considered in relation to commercialisation of science. There is a substantial increase in commercialized science due to the different factors such as economic-political, ideological, legal and scientific (see details in Irzik 2010, p. 131).

Commercialisation of science also allows scientists to find funds for their research projects while the funders increase their profits through these research projects indirectly or directly. In line with developments in commercial science, the approach to patent and rights of scientific knowledge also changed as observed in the amendments to legal rules and regulations related to patentable products. Irzik (2007) discusses the following case to clarify the changes in approaches to patentable products and rights:

> In 1873, for example, Pasteur was issued a U.S. patent for yeast culture. But the patent pertained to microorganisms within the process of fermentation, not just to the organisms themselves. However, the situation changed dramatically with a Supreme Court decision regarding Diamond v. Chakrabarty

> in 1980, a decision that opened the gate to patenting both man-made living organisms and genetic material itself. The Supreme Court ruled by a 5-4 vote that while natural laws, physical phenomena, abstract ideas, and newly discovered minerals are not patentable, artificially created microorganisms can be patented under the U.S. Patent Act, Title 35 U.S.C., Section 101. Thus, a patent was granted for a genetically engineered bacterium capable of breaking down crude oil independently of the process producing it. The majority opinion held that the bacteria was a useful "manufacture" or "a composition of matter" not found anywhere in nature (p. 139).

Based on the decision of the Supreme Court, genes, DNA and genetically modified living organisms have become patentable products (Irzik 2010). The change in approach to patentable products also affects the values and norms of science (Irzik 2007).

The preceding discussion on economics of science, as brief as it may be, leads us as science educators to question how we are addressing these debates on the economics dimensions of science in schooling. Are we, for instance, developing learners who are mindful of and knowledgeable about these issues? Does our research on science teaching and learning capture the key tenets of this discussion? How can we support the teaching of these issues in practice? The raising of the next generation of scientists is necessarily an issue of concern for many societies. One could argue that schooling should introduce students to the 'realities' of economics of science so that by the time they gain sufficient expertise in their fields, they will be well equipped to participate in the financial games of their fields. Contextualisations of NOS in the classroom, for instance, could include the teaching of patenting and property rights issues in science.

If the norms of science cannot be ignored in understanding NOS and if the financial factors play out in the production and dissemination of scientific knowledge, shouldn't these issues be captured in teaching? Aren't science teachers responsible for teaching scientific norms and values? Given the curricular expectations mentioned earlier on scientific literacy in general, and in understanding science as an enterprise in particular, it is imperative to include economic themes such as patent case scenarios in science teaching. On the other hand, science education sits in an uncomfortable place in this landscape given particular aspects of patenting and property rights imply limited access and thus inequity in knowledge acquisition. What would exactly be the goals of introducing students to the norms that surround the restriction of scientific knowledge and how would these goals relate to other goals of schooling, such as the raising of ethical and humanistic citizenship? These are important questions to consider in identifying the goals and outcomes of science education in relation to economics of science. Whilst the financial contextualisations of science in science education is an area that has been neglected, the precise ways in which these contextualisations can be operationalised are not straightforward.

## 4 Discovery Versus Invention in Science: Arguing about the Economic Aspect in the Science Classroom

One of the consequences of the commodification of science through patenting rights concerns the issue of discovery and invention in science. Irzik raises this issue as part of the rationale for why philosophers of science should pay attention to economics of science, given the long history of the distinction in philosophy of science. In illustrating the conventional thinking around this distinction, Irzik (2010) states:

> We think of the distinctions between discovery and invention, and between fact and artefact as follows: while facts are discovered, artefacts are invented; whereas facts belong to the domain of nature, artefacts belong to the domain of culture. All this suggests that the distinctions in question are ontologically grounded. However the situation is a lot more complicated than this. (p. 136)

He then continues to give examples that illustrate the dichotomy. Genes, for instance, are part of our biological make-up but they do not exist in isolated, pure form in nature. Engineered genes can lead to organisms that have designed purposes. For instance, the Harvard 'oncomouse' is a genetically modified animal that is made susceptible to cancer. Whilst mice are naturally existing organisms, does the engineered mouse become an invention and thus patentable? As educators, what themes can we extract from such instances of commodification of scientific knowledge for educational purposes? Are themes such as discoveries and inventions captured in the science curriculum broadly and in terms of their financial contexts more specifically? Is there a curricular context that would warrant their consideration for teaching and learning in actual classrooms?

We should note that there is policy and curricular imperative for the consideration of perspectives from economics of science. In many parts of the world, policy documents (e.g. OECD 2006; European Union 2006; MEC 2004) have advocated the contextualisation of science in its wider societal, cultural, political as well as economic dimensions. Consider for example the National Science Curriculum in England and Wales. The recent revisions in the national science curriculum highlight a recognition that the teaching of science has to aim not only the conceptual outcomes of science but also the social, cultural, economic and ethical processes underlying scientific inquiry (Table 1). The "How Science Works" component of the Science National Curriculum (DfES/QCA 2006) suggests the incorporation of "applications and implications of science" which encapsulates scientific debates. The reference to "data, evidence, theories and explanations" also promotes a metal-level perspective on the characterisation of science that would subsume discussions related to the distinctions of discovery and invention.

The existence of a curricular context is not necessarily sufficient for the actualisation of particular goals in science teaching and learning. Educational reform often falls short of effective implementation due to the general and broad policy level recommendations that are not coupled with instructional strategies that would help achieve particular learning outcomes. In other words, expecting teachers to teach the discovery versus invention controversy is unrealistic when they are not equipped with the pedagogical tools to transform such broad and abstract concepts for practical learning purposes. Argumentation is a strategy that could facilitate the communication of such controversies. The work broadly situated within argumentation studies in science education (e.g. Erduran and Jiménez-Aleixandre 2008) provides a framework because of the inherently oppositional

**Table 1** "How science works" in the science national curriculum and potential target skills (from La Velle and Erduran 2007)

| 2006 National curriculum: how science works | |
|---|---|
| Curriculum descriptor | Argument skills |
| Data, evidence, theories, explanations | Understanding the nature of evidence and justifications in scientific knowledge |
| Practical and enquiry skills | Justifying procedures, choices for experimental design; generating and applying criteria for evaluation of evidence |
| Communication skills | Constructing and presenting a case to an audience either verbally or in writing |
| Applications and implications of science | Applying argument to everyday situations including active social, economic and political debates |

nature of the debates surrounding the concepts of discovery versus invention. This area of research is currently drawing a lot of attention in the science education research community, being characterised as one of the top areas of research (Lee et al. 2009). Hence our reference to argumentation is also warranted from a viewpoint of consistency with contemporary work in science education research. The articulation of argumentation for educational purposes have benefited from perspectives on science drawn epistemology, linguistics, communication studies, language studies, social semiotics, developmental psychology and socio-cultural perspectives on learning (Jimenez-Aleixandre and Erduran 2008). More recent work has highlighted the neglect of the financial, political and cultural aspects of science in the framing of argumentation studies (e.g. Erduran and Jiménez-Aleixandre 2012).

Hence, the linking of argumentation work with the theoretical foundations of economics of science is likely to contribute to the understanding of argumentation for educational purposes as well. Argumentation studies in science education are relatively young (Erduran and Jiménez-Aleixandre 2012). It can be said that classroom-based research began in the 1990s. The initial set of studies focused, on the one hand, on exploring whether science classroom environments favoured argumentation, an exploration with negative outcomes (e.g., Driver et al. 2000), and on the other hand, on investigating students' argumentation (e.g., Jiménez Aleixandre et al. 2000). As the field has developed, the focus shifted towards an interest in the quality of arguments, or how to analyze the development of students' argumentation competences (e.g., Erduran 2008). In the last few years there is an emerging interest about how to support students' engagement in argumentation, through the design of learning environments (e.g., Jiménez Aleixandre 2008) and professional development of science teachers (e.g., Erduran et al. 2006; Ozdem et al. 2012).

The dichotomy presented by discovery versus invention broadly presents a context for argumentation that will be of relevance to science education. The generation and evaluation of the criteria to engage in the epistemological, ontological as well as socio-cultural and economic dimensions of discovery and invention can be positioned as learning outcomes of science. For example, if we return to the oncomouse example provided by Irzik (2010), students could be engaged in group discussions to formulate what counts as facts or artefacts in application to genes. The engagement in meta-level discussions on the nature of discovery, invention, fact and artefact in disciplinary settings where some of the boundaries might be blurred is likely to promote students' deeper understanding of not only the nature of science but also the conceptual domain itself, in this case genes and inheritance.

Whilst the financial contextualisations of NOS in science education is an area that has been neglected, the precise ways in which these contextualisations can be operationalised are not straightforward. The difficulties in distinguishing a fact from an artifact in particular domains of science are partly related noteworthy. For the purposes of instructional approaches, the imperative to have sound and clear learning objectives demands that either the ambiguities of particular distinctions are communicated to students such that they are equipped with the skills of evaluating the ontological status of the discovery versus invention debate. Even though science teaching tends to favour the definitive declarative and factual scientific knowledge, uncertainty suggested by the philosophical debates around patenting of inventions challenges the factual status of scientific knowledge presented in the classroom. Consider for example the case of organic chemistry. One could imagine that organic chemists produce materials that are available naturally but the discovery of such materials has not yet occurred through investigations into naturally existing products. In that case, would an organically synthesized artifact cease to be an artifact when the same substance is ‘discovered’ in natural form? The content of debates guided by such questions would inherently promote uncertainty and open-ended reasoning, as opposed to precise conceptual outcomes.

Furthermore, given the recent developments in patenting rights of artifacts, teachers as well as students would need to have realistic conversations around facts and artifacts. The conventional coverage of this topic in science education appears outdated. A lesson that begins to get students to understand the complexity of distinguishing facts subsequently could lend itself to the surrounding ethical and professional issues that underlie science as a social enterprise. Is it ethical to patent and sell a substance that exists? Should access to scientific knowledge be restricted on financial grounds particularly in light of the medical good that can come out of a drug that has been patented? Whilst we recognise that by promoting the existence of such questioning in the classroom, the teachers might be instilling the financial arguments in the minds of the students, we believe that the omission of these questions would be more detrimental to students’ education. If such arguments were missing in the classroom, wouldn’t the education system be doing disfavour both to the general public and the emerging scientists? How would an education system, help raise citizens who understand the complexities of decision-making around socio-scientific issues that are inherent in society? After all, if commodification of science presents issues of inequity in society, who would be in a position to challenge and reform such inequity without the awareness of its existence in the first place? Inclusion of strategies like argumentation in science classrooms begins to support teachers in structuring lessons such that debates around such questions can be raised in the classroom. We should note however that argumentation is a relatively new strategy for even experienced science teachers and careful attention needs to be placed on the professional development of science teachers to equip them with the skills to deal with the complexity of the issues represented (Simon et al. 2006).

So far, we have made a case that discovery/invention and fact/artefact dichotomies are useful examples from economics of science that can be imported for educational purposes. We have outlined an exemplary policy context that warrants the inclusions of these dichotomies in school science, and suggested that argumentation, given its inherent disputational and oppositional nature, can be a useful strategy to actualise these themes at the level of the classroom. We would now like to provide a concrete lesson example in order to illustrate how these concepts can be implemented in science lessons. The example is consistent with other examples in the research and professional development literature that highlights tested effective resources (e.g. Erduran 2006). Such resources provide the structure and the support for discussions in the classroom. Other pedagogical strategies (e.g., presentations and questioning) are needed to supplement the teaching in order for such resources to be useful for learning purposes (e.g. Erduran et al. 2006). In this activity (Table 2), students are presented with two alternative claims and provided with some statements that would help build up each claim or to refute the alternative claim. Students can be encouraged to generate their own statements and/or research information to further support their claims.

Such example activities will exploit the emergence of the key concepts in the classroom such that the economic dimensions of the issues are highlighted in ways that are not typically done in science classrooms. They can be complemented with key concept cards (Table 3) that provide further and deeper understanding of the issues.

Our example activity illustrates how the abstract concepts we have covered in this section can be transformed for concrete use in a science classroom. A significant difference of this kind of debate informed by economics of science and one, for instance, promoted by

**Table 2** Example student activity aimed at secondary schooling to promote argumentation about discovery/invention and fact/artefact themes

Student activity: Oncomouse: To patent or not?

Consider the following competing claims about a genetically modified mouse that was produced at Harvard University. The oncomouse was designed to be susceptible to cancer and it is intended to help scientists understand cancer. In your groups, discuss each claim and use the evidence statements to build up support for your claims. Some of the evidence may be relevant for one claim or the other at the same time. Some evidence may be irrelevant and some may only be relevant for one claim. Make sure that you justify why you think that the evidence goes with your claim

*Claim 1*: The oncomouse is a genetically modified animal that has been invented. It has to be patented with due financial rewards granted to its inventors

*Claim 2*: The oncomouse belongs to all humanity and science; it cannot be patented to particular individuals

*Evidence statements*

| | |
|---|---|
| Genes are made of DNA whether they are produced in the laboratory or exist naturally | Scientists deserve to patent the important discoveries and inventions they work hard at achieving |
| Science belongs to all humanity and help cure diseases | Modified genes are not the same as naturally existing genes |
| The mice and human beings are very different genetically. There is no use in researching cancer in mice to help humans | All governments should have policies to control scientists and what they do |
| An invention is something that does not occur naturally | All citizens in a democratic country have the right to own property |
| Patents are for commerce, not for science | Everything comes with a price in life |
| Genetically modified genes that cause cancer are not the same as naturally existing genes that cause cancer | Scientists are human beings who have to survive and need money to live |
| The oncomouse may have modified genes but it is still an animal | Modified genes are discoveries about how genes can behave in different circumstances |
| Cancer is a disease with a market | There is great demand for the treatment of cancer |
| The oncomouse will help us become more productive in dealing with human fatality due to cancer | It is unrealistic to expect that science is free from commercialisation in this day and age |
| If you want to be treated of cancer, you need to pay for it | If we patent the oncomouse, this will help scientists to be competitive in the market and produce better discoveries |

**Table 3** Key concepts to complement the oncomouse activity

| Key concepts | |
|---|---|
| Markets: are the systems, institutions, procedures and social relations by which people exchange goods | Commercialisation: is the process of introducing a new product or process into the market |
| Supply: is the amount of product that is available to customers | Demand: is the desire to own something and pay for it |
| Growth: is increase in quantity over time | Commodity: is an item that can be produced to satisfy the needs and wants of a market |
| Productivity: is a measure of the efficiency of production. It is a ratio of production output to input | |

the SSI literature is that there would be an explicit reference to the concepts of economics, with precise articulation of the source, the terminology and the context of the economic debates. The very framing of this activity is sensitive to the grounding of the involved concepts in the literature on economics of science. Hence, there is theoretical rationale and link in the design of the task. Contrary to a typical SSI scenario, apart from the ethical and societal aspects of a similar debate, there is firm emphasis on the economic nature of the issues involved. In other words, the reference to economics is not on general grounds but rather is characterised through explicit import of concepts and issues raised within economics of science itself.

We conclude this section by stressing that the inclusion of perspectives from economics in science teaching and learning is not intended to bias a particular perspective. We believe that the decision for such a perspective rests on the learners themselves. Our intention is merely to encourage informed discussions in the classroom such that the economic dimensions of science can be interrogated in ways that are not typically done in regular classrooms.

## 5 Models and Modelling in Science Education: An Economics Perspective?

There are different senses in which models and modelling can be conceptualised in science education research. At a broad level, one could define a "model of science" that aims to define and exemplify the nature of science itself. For instance, the philosopher Ron Giere's model-based view of science is an epistemological account of a model (Giere 1997) that aims to illustrate how science works. It is a perspective that has been discussed widely in science education research (e.g. Aduriz-Bravo 2013). Science education could subsequently use such models of science in its efforts to embed a particular version of science in science teaching and learning. A second sense of models concerns the particular instances of models within scientific knowledge, such as the model of the solar system, which aims to help understand natural phenomena. This is a "models in science" perspective where different characteristics of models are interrogated and investigated (e.g. Woody 2000). A third sense of models has to do with the ways in which characterisations of models are imported for use in science education from a range of perspectives including cognitive psychology and philosophy of science (e.g. Erduran and Duschl 2004), and examined for their conceptualisation for a theory of pedagogy (e.g. Gilbert and Boulter 2000). This is a "models in education" perspective where other senses of models might be subsumed and others such as pedagogical models are extended in order to develop understanding of teaching and learning processes.

When reviewed in science education, the above senses of models tend to emphasize the philosophical, cognitive, pedagogical and social aspects of models and modelling. Even the scarce reference to interdisciplinarity (e.g. Erduran and Duschl 2004) in relation to models does not make reference to any economics characterisations of models. Our intention in this section is to provide another example of how economics of science and science education could interact by illustrating a models and modelling perspective informed by economics of science.

In "model of science" sense, Radder (2010) distinguished three ideal–typical models of science from an economics perspective: commodified science, autonomous science and public interest science. *Commodified science* refers to the economic instrumentalization of science. *Autonomous and public interest science* emphasize criteria other than economics such as development of the society or development of science itself. Autonomous science illustrates an independent scientific community whereas public interest of science frames the function and the role of scientific community with solving or relieving the problems of society. The *commodified science* model lends itself to a set of ideas that would have relevance in science education. First, the analogy of "science market"—where scientific ideas, concepts and knowledge as well as the technological outputs and tools are traded-can be said to be reproduced at the level of schooling. Second, scientific knowledge as commodity or as "the product of a collective human enterprise to which scientists make individual contributions which are purified and extended by mutual criticism and intellectual co-operation" (Ziman 1991, p. 3) extends the rational conceptualisations of scientific knowledge to situate as a product of commerce. Third, some of the conventional boundaries between scientific endeavour and the societal and cultural norms that surround science could be argued to dissolve through articulations stemming from the "science as commodity" idea. Indeed from this perspective, "science (can) no longer is regarded as an autonomous space clearly demarcated from the 'others' of society, culture and economy. Instead, all these domains have become so internally heterogeneous and externally interdependent, even transgressive, that they cease to be distinctive and distinguishable." (Nowotny et al. 2001, p. 1).

Economics of science articulates science at large, demonstrating different models of the scientific enterprise given certain financial dynamics. Such conceptualisation of science can lead to the envisioning of science education as a sub-market of the broader enterprise. We can also argue that the science classroom is an example of a sub-market of science where scientific knowledge is exchanged and traded. Here we are referring to the first sense of models as described above. If we took the market metaphor further and applied it to the conventional coverage of models in science education, we can begin to develop a new positioning of models, which has drawn substantial amount of work in science education research (e.g. Gilbert 2004). We do not wish to conflate these different senses of models. i.e. model of science as commodity ("models of science" sense), the ways in which scientists themselves model natural phenomena to understand their nature ("models in science" sense) and the educational instantiations of a range of models ("models in education"). However as educators, we are interested in synthesising a coherent perspective for science education that would be mindful of the ways in which these senses of models can be operationalised in education.

Our choice of 'models' as another example to investigate the implications of economics of science in science education rests on the extensive literature in science education research that has illustrated the presence of various kinds of models that are relevant for pedagogical purposes. The coverage of models in science education illustrates the diversity of models embodied in learning, teaching and curriculum. However, often these kinds of models are treated as discrete categories that are in interaction solely as epistemic, cognitive or pedagogical categories. The economics perspective, particularly the commodified science model itself lends itself to a reconceptualisation that facilitates the understanding of some dynamics that are of concern to science teaching and learning. The 'market' metaphor exposes those processes and dynamics that might hinder the inclusion, acceptance or rejection of ideas in the classroom.

In the following paragraphs, we will review some of the typical coverage of models and modelling in science education research for two reasons. First, we would like to illustrate how they are situated in this domain, which will show that there is no consideration of science from an economics perspective in the characterisation of models. The second reason is that we will then use aspects of this literature to synthesise a perspective that will extend this literature with contributions from economics of science considerations. Models are significant tools in science and science education in order to explain natural phenomena. For instance, in the context of chemistry the fundamental concepts such as atoms and molecules, by definition, are models. Inevitably, chemistry curriculum and chemistry lessons consist of models. Erduran and Duschl (2004) exemplified the presence of models in chemistry classes by referring to models of acids and bases, the 'affinity corpuscular' model, 'thermodynamics' model, 'kinetic' model and so on. Scientists construct models so as to explain, make predictions and control the natural world (Gilbert et al. 1998). Specifically, chemists' models are to explain both the physical and chemical properties and transformations of materials in pursuit of scientific aims (Justi and Gilbert 2002). Coll et al. (2005) exemplified the use of models to explain macroscopic nature of substances as follows:

> As soon as scientists attempt to explain macroscopic nature (e.g. physical and chemical properties of substances, chemical behavior) they inevitably resort to the use of models. Thus, models and modeling are key features of science and consequently of science education when there is an attempt to make accessible scientist' understanding and to provide some insight into their business. (p. 135)

Yet the meaning of the term 'model' or its functions are not so straightforward. The presence of models in different disciplines such as cognitive psychology, philosophy of science, chemistry or education makes it even more difficult to come up with a single definition for the term "model". Erduran and Duschl (2004, p. 111) discussed three different definitions of models in chemistry, for example. The term model can refer to "a material object, such as a construction". For example a chemist can construct a model to represent the structure of a molecule so as to explain the motions of the atoms in the molecule. Another definition involves the model as "a description, an entity that is merely imagined and described rather than to one is perceivable". Finally a model can be defined to involve a system of mathematical equations so as to "give exactness to the description" such as developing a model considering the wave-equation for a hydrogen atom.

Apart from the various definitions of models, researchers in science education have also highlighted different kinds of models. Gilbert (2004) outlined a range of models that need to be differentiated for pedagogical and learning purposes. A mental model is "a private and personal representation formed by an individual either alone or in a group" (p. 118). If a mental model is presented then it is called an *expressed model*. The construction of a mental model and its transformation into an expressed model is also recognised as an aspect of learning science. The sharing and discussion of a model might end up with an agreement yielding what is called a *consensus model*. If a model is approved by a scientific community, then it can be classified as a *scientific model*. Another version is *historical model*. In the history of science, some of the scientific models were replaced with others in light of new evidence that led to the construction of new models. There are also different types of representations of models such as material, verbal, symbolic, visual or gestural modes (see the examples in Gilbert 2004). Some of the presentations of scientific or historical models are simplified for educational purposes. These are then called *curricular models*. The educational context also relies on *teaching models* that foster science learning and *hybrid models* that they involve infused characteristics of different models.

As emphasized by Carr (1984) "clear indications of *when* a new model is being introduced, of *how* this new model differs from previous models and of *why* the new model works better would seem to be vitally important in the teaching process" (p. 99). Despite long-standing work in the modelling literature in science education research, how the various types of models can co-exist or are positioned for educational purposes has not been considered from an economics perspective. Let's examine how some key terms from economics such as "knowledge as commodity" and "class" can help clarify how and why various iterations of scientific knowledge are treated in the classroom. For example, in the "modelling market" of the classroom (Fig. 1), the range of models will be manifested, debated, contested and appropriated. The expressed models will interact with curricular

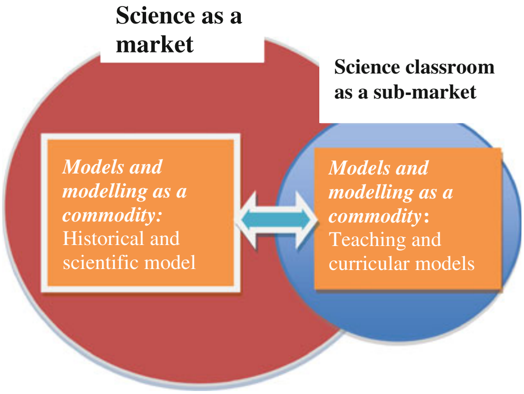


**Fig. 1** The trade of models and modelling in the science market and the submarket of the classroom

models. Sometimes there will be consensus models, other times scientific models might dominate at the expense of children's mental models. In this respect, models will be commodified for exchange, sharing or disposal. The teacher's models will have more currency than the students. A particularly problematic aspects of models in circulation in the classroom concern hybrid models, essentially a sub-market of models. Hybrid models that do not exist in contemporary science or in the history of science may appear in educational settings and may lead to misconceptions. Hybrid models in the teaching acids and bases from secondary school and university chemistry textbooks are good examples of such models (Carr 1984). Some researchers have strictly advocated that hybrid models are to be avoided in teaching since they lead students to have misconceptions in their mental models of the theme being discussed and/or to have difficulties in understanding the reasons for which hybrid relationships are introduced (Justi 2000).

Figure 1 illustrates our interpretation of the trade of models and modelling from the science market to the science classroom as a sub-market of the scientific endeavour. For pedagogical purposes, *scientific* and *historical models* are transformed into *teaching* and *curricular models* in the science classroom. Hence, curricular and teaching models can, in principle, be consistent with the scientific and historical models. On the other hand, hybrid models "have no genuine historical provenance" (Justi and Gilbert 2003, p. 1370) and they make it difficult to understand scientific processes (Justi 2000). In this sense, emergence of hybrid models in science lessons is not a result of a trade of models and modelling from the science market but rather through other classroom related markets, primarily through students' own conceptions of and in science, as well as their everyday experiences with the world outside of the classroom.

Science teachers, students and the public demand scientific knowledge for various reasons. Within the limits of science education, we call these groups as naïve demanders because scientific knowledge is exchanged only for teaching and learning purposes. However, these groups are usually the end users of scientific knowledge and therefore do not have access to the latest scientific knowledge, which is not yet accessible to third parties.

Hence the presence of barriers implies that there is potential conflict of interest between the main funders of scientific knowledge and its naïve demanders. A good example is from genetics. Genetics is one of the subjects that rapidly commercialized in US (Irzik 2010). Both governments and private firms provide funding for the development of scientific knowledge in genetics, which substantially supports the theory of evolution by natural selection. This example can also be understood from the perspective of commodified science model. There are both public and private funders of the intelligent design propaganda for the end users. For this potential conflict between naïve demanders and funders, science teachers have a crucial role in influencing what gets projected as scientific knowledge in the classroom. Teachers have to demand real science and scientific knowledge. They have to demand to have access to the latest scientific knowledge. The barriers that hinder free access to scientific knowledge emerged with the commodified science. The sensitive balance between raising the students' awareness of competing political, religious and financial agendas, and taking care of not fostering the institutionalisation of the very norms that hinder access to scientific knowledge will inevitably be challenging for science teachers. Contemporary science teacher education initiatives would benefit from the articulation of such issues in order to inform teachers' awareness and skills in teaching science in its economic context.

Our discussion of models exposes a particular orientation to models in science education that has not previously been discussed from an economics perspective. We have repositioned the way that models and modelling have been discussed by (a) broadly highlighting science as an economic enterprise and the science classroom as a sub-market that is influenced by this enterprise, often in quite an indirect and delayed fashion, considering barriers in access to new knowledge, and (b) more specifically in illustrating the dynamics of models in teaching and learning, including the variations of scientific, historical and hybrid models. Our interpretation, using the market metaphor, of how models are treated in school science suggests why particular ideas might be resistant to change in the classroom while others prevail. The economics perspective provides a new lens through which the dynamics of models and modelling in science classrooms can be interpreted.

## 6 Conclusions and Implications

In this paper, we have argued that the theoretical grounding of science in science education could be extended to include perspectives from economics of science. We have illustrated how the commodification and commercialisation of science can be considered in relation to science education in the context of examples such as patents and the metaphors of "market and sub-market" to illustrate the dynamics of knowledge exchange and trade at the level of the classroom between teachers and students, in this case in the treatments of models. We have also extended our discussion to consider particular applications such as the learning outcomes in terms of articulation of the complexity of debates surrounding discoveries and inventions in science, and their contextualisations in the financial world of science. We have presented a concrete example that secondary school science teachers can use to support their students' debate about the commodification of genetically modified organisms. The proposed activity is conceptualised with due consideration of the effectiveness of similar tested frameworks on argumentation. Our framing of the research on models and modelling in science education offers a new lens for interpreting the various kinds of models through the market metaphor. Our intention here was to illustrate a potential step forward in theoretical interpretation of model use in science education. Our discussion is inherently and admittedly limited in that we are choosing several examples in this paper to link economics of science and science education. Future work in science education would benefit from further explications of these themes not only for theoretical purposes but also for the aim of conducting school-based research to gain empirical insight into the operationalisation of these concepts.

We are mindful of the sensitivities surrounding the import of economic perspectives in science education. Jacob (2003) argues that commodified science is “a threat to the autonomy of science, and autonomy as a precondition for the production of high quality knowledge” (p. 140). Furthermore Irzik (2007) discusses how Merton’s widely accepted norms of science, which guide the work of scientists, are being threatened by the growing dominance of financial forces in the scientific endeavour. These norms include universalism disinterestedness and communalism. According to universalism, the criteria of science are objective and independent from the characteristics of scientists such as gender or ethnic origin. Moreover, scientific research is pursued independently from personal interest and ideologies. This is called disinterestedness. As for communalism, scientific knowledge does not belong to an individual or an institution as a private good. Specifically, scientific discovery or knowledge must be considered as public good which is ‘nonrival’ and ‘non-excludable’.

These norms should accompany the policy calls that have long been advocating the position that science students should not be led to believe in idealisations, myths and reductive approaches in science. For example, the National Science Education Standards (National Research Council 1996) suggests that school science must give students an opportunity to experience science authentically, free of the legends, misconceptions and idealizations inherent in the myths about the nature of the scientific enterprise. Likewise, there must be increased opportunities for both pre-service and in-service teachers to learn about realistic accounts of the nature of science, which are often quite complex. Our discussion on the economics of science begins to provide some guidelines for which aspects of science from this perspective can be operationalized for theoretical and practical purposes. For example, the concept of “scientific knowledge as commodity” lends itself to debates on why particular aspects of science (i.e. scientific models) are to be “traded” in school science but not others (e.g. hybrid models). Any potential conflict between the funders of the science and science classroom may result with appearance of the pseudo-scientific issues in the science classroom.

In conclusion, our goal in this paper was to draw out some ideas from the growing body of work in economics of science (e.g. Nowotny et al. 2001) to explore the implications for science education. The work is situated within the agenda of applying interdisciplinary perspectives on science from foundational disciplines in order to inform science education. In terms of research domains in science education, we have chosen to explore some preliminary implications for modelling, an area with substantial empirical foundation in science teaching, learning and professional development. We have linked the currently prominent research area of argumentation to synthesise a framework that makes use of economic ideas for practical teaching purposes. Future work in economics of science could also potentially be informed by research offered by science education. By highlighting some examples of the pedagogical aspects of teaching economics concepts through argumentation as well as the typology of models and modelling from a science education research perspective, we hope that we can initiate a constructive interdisciplinary and reciprocal debate between science education and economics of science.

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