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Epistemology, Sociology and Learning and Teaching in Physics

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Abstract

This paper explores the relationship between epistemology, sociology and learning and teaching in Physics based on an examination of literature from research in science studies, history and philosophy of science, and Physics pedagogic research. It reveals a mismatch between the positivist epistemological foundation which seems to underpin the teaching of Physics at undergraduate level and the tentative nature of knowledge and the primarily social-constructivist process of knowledge creation which characterise the practices of professional physicists. Attention is drawn to the consequences of neglecting this mismatch, detrimental to students' understanding of the nature of the discipline, their conceptual development and the acquisition of skills essential not only for a scientific career, but also for students' development as individuals and citizens. The paper argues for the explicit contemplation of disciplinary epistemology in Physics teaching and in pedagogic research to improve student learning, while avoiding the dangers of epistemological essentialism.

Keywords: pedagogy; epistemology; sociology; learning and teaching; Physics; disciplines; higher education.

1. Situating Physics learning and teaching in context

The role of disciplinary characteristics, epistemological or sociological, in shaping higher education pedagogy has received little attention (Hativa and Marincovich, 1995; Krause, 2012; Kreber, 2009; Neumann, 2001; Trowler et al., 2012; Ylijoki, 2000). Learning and teaching in higher education Physics has been discussed by McDermott and Redish (1999), Redish (2003), Redish and Steinberg (1999), Tobias (1992) or van Heuvelen (1991), to name but a few. The American Institute of Physics (AIP)'s conferences also provided a wealth of resources on Physics learning and teaching (Engelhardt, Churukian and Rebello, 2012; Redish and Rigden, 1996). Additionally, the results of the pan-European Tuning project, advocating pedagogic approaches grounded in the development of student competences (Tuning Project, 2008), or the resources of the Physical Sciences Centre in the UK[1] have proposed innovative pedagogies for improved student learning. However, the relationship between pedagogy and epistemological aspects, i.e. how epistemology informs (or can inform) learning and teaching, has been addressed to a lesser extent. Matthews (1997), for instance, discussed

[1] http://www.heacademy.ac.uk/physsci/ accessed on 2 August 2013

the rise of constructivism as a new pedagogical paradigm towards the end of the 20th century and presented various viewpoints about how this approach reflected the epistemology of science. Some more concrete examples of the integration of epistemology in learning and teaching have been provided by: an account of how technoscience, a reconceptualised epistemological foundation for Physics through its unification with technology, can be used in order to improve teaching and learning (Tala, 2009); a parallel between the epistemology of modelling, which illustrates the transition from abstract to concrete, and science teaching (Sensevy et al., 2008); a reconstruction of the epistemology of experiments with positive effects for students' learning and their own construction of knowledge (Koponen and Mäntylä, 2006); a theoretical framework for an epistemological modelling of teaching-learning sequences which draws on studies of scientific practice, since understanding science implies some understanding of the practices involved in scientific inquiry (Psillos, 2004).

While considering pedagogy in relation to disciplinary epistemology, such suggestions seem to invite the harmonisation of learning and teaching in Physics with the nature of knowledge and the process of knowledge creation characteristic of the discipline with a view to enhancing student learning. They could be seen as responses to traditional instruction and the knowledge transmission model, still prevalent in the teaching of Physics (Redish and Steinberg, 1999; Thacker, 2003; DeHaan, 2005). A survey in the United States found that only a minority of students engaged with active learning or real-world problem solving in their introductory science courses; in the majority of cases, the typical practice was the lecturer delivering information (DeHaan, 2005). This conventional pedagogy came under criticism further to concerns that it was not effective in developing students' understanding, urging reforms in science education in general, Physics included (DeHaan 2005; National Science Foundation, 1996; Redish and Steinberg, 1999; Taylor et al., 2002; Tobias, 1992). Calls have been made to move away from lectures and to provide increased opportunities for students to discuss aspects related to disciplinary content and nature, building on constructivist principles. Having started to exert influence on science education at the end of the 20th century, constructivism purported that meaning construction takes place during students' interaction with the environment and advocated students' active experience with the physical world (Matthews, 1997).

Reform attempts in Physics pedagogy have gained expression in what has come to be known as 'physics education research', spurred on by gaps identified between instructors' expectations of student learning outcomes and actual conceptual understanding. However, physics education research has gone beyond highlighting the shortcomings of traditional instruction, giving rise to examples and proposals of innovative pedagogic methods (Heron and Meltzer, 2005). Indeed, Physics has been a pioneering discipline in pedagogic improvement, with many innovations having started here (DeHaan, 2005). In this respect, a comprehensive review of advances in classroom Physics (Thacker, 2003) noted that curricula and courses had been redesigned with an increased attention to: conceptual understanding and the cognitive skills required to understand and apply Physics concepts; attractive teaching environments and situations (such as 'real-life' applications, hands-on environments, teaching modern Physics and quantum mechanics concepts earlier in the curriculum); interactive engagement of students; and the use of technology. Concrete suggestions and examples of alternative pedagogical methods abound in literature: problem-based learning as a 'powerful alternative' to the passive lecture in introductory courses (Allen, Duch and Groh, 1996); 'interactive engagement' strategies, claimed to be more effective than traditional passive methods in enhancing students' understanding in conceptually difficult areas (Hake, 2002); enhancement of students' learning through participation in classroom demonstrations as opposed to acting as passive observers (Crouch et al., 2004); a grounded theory for students' construction of knowledge, including talk and writing strategies, to facilitate understanding of science concepts (Syh-Jong, 2008); a design of teaching sequences based on a social constructivist perspective of learning, consisting of three phases: staging the scientific story; supporting student internalisation; and handing-over responsibility to the students (Leach and Scott, 2002). These are only a few illustrative examples, since documenting extensively the efforts to innovate Physics pedagogy lies outside the scope of this paper. Yet, despite advances in the teaching of Physics, there has been no wide-ranging progress in the way university courses are taught at most institutions; instead, changes have been very local, specific to a university or to a particular professor (Thacker, 2003). This is the reason why, when discussing pedagogy, the focus of this paper lies on traditional instruction methods, while acknowledging the recent developments in the context of physics education research.

Against this backdrop, the paper seeks to bring loose ends together and explore the relationship between disciplinary epistemology, sociology and pedagogy, with a view to understanding how this relationship influences student learning at the level of curriculum content, knowledge transmission and acquisition, conceptual understanding, generic skills[2] development, assessment, research training and so forth. It argues for the integration of epistemological and sociological considerations in the teaching of Physics further to observed disparities between the process of science-making and the practices of professional physicists social constructivist in nature, on the one hand, and undergraduate pedagogy generally informed by a positivist epistemology, on the other hand. Disregarding this mismatch, it is argued, has negative consequences for students' understanding of the nature of the discipline, their conceptual development and the acquisition of skills which are essential not only for a scientific career but also for students' development as individuals and citizens.

The paper starts by delineating some key concepts – epistemological essentialism (Trowler, 2013), classification and framing (Bernstein, 1971) – which serve to describe disciplines and disciplinary practice and can help articulate the link between disciplinary epistemology, sociology and pedagogy in Physics. Next, these three

[2] Generic skills or attributes are understood here as student skills or attributes assumed to transcend the disciplinary context, transferable from one context to another, for example critical thinking, problem solving and communication (Jones 2009b). However, Jones reconceptualised these as 'discipline knowledge in action', an expression of the relationship between knowledge and the world, the application of knowledge to theoretical or practical problems, and the organized expression of that understanding.

dimensions – epistemology, sociology and pedagogy – are analysed in turn. First, the paper discusses the existence of conflicting epistemologies – a positivist view of Physics versus a social-constructivist, relativist one – both from a history and philosophy of science perspective and based on scientists' views of the nature of science explored by research in science studies. Second, in moving on to the sociology of Physics, it is noted how its sociological aspects support a social constructivist epistemology. Sociology is explored with respect to three dimensions: scientific activities which result in knowledge creation and validation; social patterns of interaction among physicists; and wider societal issues related to the underrepresentation of some social groups in Physics. The sociological insights acquire relevance because they challenge traditional views on the nature of science based on a positivist epistemology. Third, attention turns to learning and teaching and the relationship with the epistemology and sociology of Physics discussed in the previous sections. The analysis reveals a mismatch between contemporary views on the nature of science and the process of knowledge production, primarily of a social-constructivist character, and pedagogical choices mostly based on positivist principles, showing a variety of aspects in which this inconsistency can be detrimental to student learning and development. Last, the paper concludes with a synthesis of the insights gained and makes some recommendations for pedagogic practice: the incorporation of epistemological and sociological considerations in learning and teaching to better reflect the evolution of the Physics knowledge corpus and professional physicists' practices of knowledge creation; and the rejection of disciplinary essentialism based on positivist views of science in teaching, which fails to develop competent scientists and critical, discerning individuals.

2. Physics seen through the concepts of disciplinary essentialism, classification and framing

2.1 Epistemological essentialism

This study draws on literature which addresses the characteristics of Physics knowledge (epistemology), the sociological and social aspects of Physics (sociology) and learning and teaching aspects (pedagogy). In bringing together these three dimensions and analysing their interconnectedness, the paper distances itself from epistemological essentialism (Trowler, 2013), i.e. a deterministic relation between knowledge characteristics of a discipline and academic (and other) practices. Epistemological essentialism stresses the homogeneity of specific disciplinary features, acting as unique identifiers which mark each discipline as being itself. It also bestows upon disciplines generative power, that is, its essential knowledge properties are claimed to generate, directly and universally, specific characteristics and practices among disciplinary practitioners, including at the level of pedagogy (Trowler, 2013).
Such an example of epistemological essentialism is provided by the description of Physics as a hard-pure discipline in Becher and Trowler's (2001) work on academic tribes and territories, which has acted as a reference for much subsequent pedagogic research. Physics is argued to be hard (versus soft) on account of its clear paradigm, i.e.

the consensus among the discipline's constituency on its epistemological territory and the methods of knowledge production, and pure (versus applied) on account of its focus on theoretical knowledge rather than practical knowledge application. As a hard-pure area, it is described as follows:

> cumulative; atomistic (crystalline/tree-like); concerned with universals, quantities, simplification; impersonal, value-free; clear criteria for knowledge verification and obsolence; consensus over significant questions to address, now and in the future; results in discovery/explanation (Becher and Trowler, 2001, p. 36).

Nevertheless, epistemological essentialism has been challenged by theories which acknowledge that a multiplicity of factors, for example social and individual ones, influence learning and teaching practices (Trowler et al., 2012). Social-constructionist theories argue that disciplines contain several narratives, constructed in specific contexts, shared and developed over time (Lindblom-Ylänne et al., 2006; McCune and Hounsell, 2005), while individual agency theories suggest that individuals, through belief, decision and action, shape disciplinary structures and practices (Hativa and Goodyear, 2002). Krause (2012), too, argues that traditional territories and tribal boundaries are becoming increasingly blurred, noting variations in the sense of belonging to disciplinary teaching communities. Therefore, in looking at Physics epistemological features and their influence on pedagogy, this paper does not suggest these are exclusive determinant factors. Instead, it will challenge the essentialist description purported by Becher and Trowler (2001), drawing on evidence from the history, philosophy and sociology of science and from research in science studies.

2.2 Classification and framing

Additionally, Bernstein's concepts of classification and framing (Bernstein, 1971; 2000), both related to educational knowledge, have relevance to the understanding of the relationship between epistemology and pedagogy. *Classification* refers to the separation and the strength of boundaries between the contents of discrete knowledge areas; it can be strong when areas are 'well insulated from each other by strong boundaries', or weak when the insulation between contents is reduced because the boundaries between them are blurred (Bernstein, 1971, p. 49). Whereas classification, in dealing with knowledge areas, has relevance for epistemology, framing describes pedagogy and the imparting of educational knowledge. *Framing* characterises teachers' and learners' degree of control over the selection, organisation and pacing of the knowledge transmitted and received in the pedagogical relationship as regards the options available to teachers and students. When strong, it entails reduced options; when weak, it entails a range of options. (Bernstein, 1971, p. 50).

Wide agreement over what constitutes the core knowledge of Physics (Becher, 1990; Becher and Trowler, 2001; Cole, 1992; Kekäle, 1999) – also conveyed by the concept 'community consensus knowledge base' (Redish, 1998) – would suggest that Physics is a strongly classified discipline, according to Bernstein's classification concept. Yet, consensus does not apply to science in the making, since at the research frontier competing theories dispute what nature's laws are (Cole, 1992). Regarding the strength of boundaries, Becher (1990) lists some limited overlap between Physics and Engineering (solid-state materials) and Physics and Biology (the structure of proteins), as well as between theoretical Physics and Mathematics. However, these are deemed to be exceptions, contrasts being overall clear. Nonetheless, with the sophistication of knowledge, disciplines have become increasingly intertwined and an 'extraordinary confluence of disciplines' (Galison, 1996) has taken place since the mid-20th century. The simulated realities in the Monte Carlo experiments are a telling example: 'part of mathematical statistics and yet often classified as part of physics... not quite pure mathematics, not quite just part of nuclear weapons design, yet perhaps, simultaneously both these and more' (Galison, 1996, p. 15). Another example of confluence is the integration between technology and science in Physics experimentation, rendered by the concept 'technoscience' (Tala, 2009), to capture the unifying view of Physics and technology in light of the cognitive role of technology in knowledge construction through experimentation. The increasingly interdisciplinary nature of scientific endeavours, therefore, implies perhaps a tendency towards a weaker classification of Physics than that suggested by some scholars. Connections with other disciplines have multiplied and strengthened through more frequent interdisciplinary research and teams working together.

Moreover, Bernstein (1971) highlights the acute sense of identity and community belonging encountered in classified knowledge areas. However, Physics does not appear all homogenous and conflict-free, containing divisions despite apparent unity. Various cultures and traditions exist within Physics, meeting around 'trading zones', in continuous transformation (i.e. the changes brought by the advent of the computer in the physicists' work and identity), but whose overlap has been essential to the discipline's continuity and evolution (Galison, 1997). In fact, disagreements appear to have favoured advances in the field: its evolution has not been 'a smooth striding forth, but a survival of errors, a series of revolts and revolutions, and thus also a history of forgetting and suppression' (Lepenies, 2006). The development of science not through a linear evolution whereby one theory builds upon another, but through fractures, with one paradigm replacing a previous one (Cole, 2006; Galison, 1997; Kuhn, 1962; Lepenies, 2006) represents another argument for the rather weak classification of Physics at its knowledge frontiers.

However, core knowledge does enjoy consensus and this translates into curricular coherence at undergraduate level (Cole, 1983; Kehm and Eckhardt, 2009). As testified by a survey of 152 Physics bachelor programmes (Kehm and Eckhardt, 2009), undergraduate curricula are rather similar in different European countries, aiming to build a foundation of Physics knowledge and methodologies, illustrative of strong classification. The survey found that the first two years of a Bachelor programme in Physics tended to be rather similar everywhere, 'because students have to be familiarised with the tools of the trade and the subject matter'. The third year of the programme is usually dedicated to project work enabling a certain degree of specialisation (Kehm and Eckhardt, 2009, p. 18). As to framing (Bernstein, 1971), very likely because of existing consensus over core knowledge and what students should cover, this appears relatively strong in undergraduate education, manifest in the selection and organisation of knowledge (Cole, 1983; Becher, 1990; Kehm and Eckhardt, 2009). However, weaker classification and framing were found in graduate programmes, characterised by specialisation and a pronounced research orientation (Kehm and Alesi, 2010). This gives more control to academics over the programmes' direction, and to students over their specialisation.

The next sections discuss the epistemological and sociological aspects of Physics, followed by an analysis of their expressions in teaching and learning. Equipped with the insights gained during the analysis, the paper then returns to the concepts of disciplinary essentialism, classification and framing and their relevance to the appreciation of the relationship between the three dimensions (epistemology, sociology and pedagogy).

3. Conflicting epistemologies

Epistemology as a sub-field of philosophy is concerned with knowledge, specifically *what* we know and *how* we know it. Hofer and Pintrich (1997) refer to these two dimensions as the *nature of knowledge* (what one believes knowledge is) and the *nature or process of knowing* (how one comes to know). These dimensions represent our reference in the examination of Physics knowledge and the methods for its creation and validation.

3.1 Positivism versus constructivism

Becher and Trowler's (2001) description of Physics as a hard-pure discipline, presented earlier, denotes a vast disciplinary area preoccupied with uncontroversial, context-free knowledge, whereas the process of knowing is characterised by objectivity, discovery and logic. It appears to lean excessively on a positivist epistemology of Physics. However, alternative claims from the history and philosophy of science and findings from research in science studies suggest that Becher and Trowler's essentialist depiction might need reviewing. For example, social constructivism, a perspective in the sociology of science which gained momentum in the last decades of the 20th century, claims that it is not nature's laws which determine the intellectual content of science, but that science is socially constructed in the laboratory by scientists and that local contextual conditions shape scientific practice (Brannigan, 1981; Cole, 1992; Fine, 1996; Latour, 1987; Pickering, 1984). A powerful metaphor to suggest the man-made, subjective nature of science is the golem, a Jewish mythology creature 'of our art and craft', 'a humanoid made by man from clay and water' (Collins and Pinch, 1993, pp. 1-2). Similarly, science studies have challenged traditional claims that science is value-free and universal and have contextualised science historically and culturally. Our representations of the world at any point in time are but 'stations along the chain of experience', which through successive rectifications lead to revised versions (Latour, 2008). For Latour, time, rectification, instruments, people and institutions are the 'very stuff' of science. Thus, in looking at the dynamics of scientific work and how knowledge claims emerge from scientific practice – moulded and constrained by cultural norms and values, organisational and institutional structures, economic and political power relationships, interests and so on – science studies have emphasised the socio-cultural dimension of scientific knowledge construction (Collins and Pinch, 1993; Galison and Stump, 1996; Stump, 1996; Knorr-Cetina, 1995), an aspect to be dealt with further in section 4.

Such conflicting views about the nature of knowledge and its creation process suggest the existence of Physics epistemologies at odds with each other. According to a positivist view, the knowledge corpus of Physics consists of objective natural laws; according to constructivist views, of socially-constructed artefacts. In the following, practising scientists' views on the nature of science are briefly explored to get a perspective from disciplinary 'insiders'.

3.2 Practising scientists' epistemologies

The existence of parallel epistemologies can be explained through the historical evolution of the views on the nature of science. In Physics epistemologies have changed over time through the shift from a classical deterministic approach to a quantum indeterministic conceptualisation of the discipline (Abd-El-Khalick and Lederman, 2000). However, although epistemological views appear situated primarily in a historical context (as discussed in section 5.1), both positivist and constructivist positions are still encountered nowadays among practising scientists. On the one hand, vehement arguments deny that scientific truth should be relative to a given local and social framework (Kragh, 1999). According to such positivist opinions, unexpected discoveries (i.e. Rontgen's discovery of rays) or quantitatively precise and confirmed predictions (i.e. the discovery of Neptune) act as evidence that objects or phenomena exist in the natural world. Therefore, although discovery is a social process, discovered objects are 'parts of nature and cannot be negotiated away if the scientists should so decide' (Kragh, 1999, p.6). Positivist views were also revealed by a study into the views on the nature of science of twenty-four scientists from various disciplines (Schwartz and Lederman, 2008): nine of these suggested either that science attains certain absolute knowledge or that science progresses nearer and nearer to certain knowledge through pure discovery, dismissing interpretation as unnecessary. While finding variation among scientists' views, no overarching pattern was noted to suggest a predictable relationship between discipline and expressed views. At the opposite end, some prominent scientists' accounts on their views of knowledge and science (Wong and Hodson, 2009; 2010) indicate that these believe scientific theories to be human constructions, created, sustained and modified through social processes. However, for these scientists, scientific knowledge goes beyond being a mere social construct; at the same time, they believe in the rationality of science, and all view it as true everywhere, at least in relation to established knowledge (what we earlier referred to as the disciplinary consensus over core knowledge). In a similar vein, another study (Yore et al., 2004) found that the scientists whose views of science were explored held 'evaluativist' views and rejected absolutist or relativist extremes. They described science in terms of arguments, hypothesis testing, or tentative science. Among physicists, a consensual epistemological adherence does not appear to be shared either, as testified by Barad (2007), Galison and Stump (1996) or Pickering (1995). In an acute form, this is demonstrated by the disagreements about the epistemological interpretation of quantum mechanics: Niels Bohr's or the Copenhagen interpretation versus Bohm's one (Cross, 1991; Freire, 2003).

A fact to bear in mind, however, is that practising scientists usually do not ponder consciously on their epistemological stance, but concentrate instead on their everyday practice. 'Privileged access' to what their practice entails does not imply a similar level of access to its epistemological underpinnings (Abd-El-Khalick, 2011). This invites the consideration of other sources of evidence, such as the scientific process of knowledge creation, to get further insight into the discipline's epistemological foundations. The process of science making in the laboratory has been the object of microsociological studies of science, which will be discussed next alongside other socio-cultural aspects of Physics.

4. Socio-cultural aspects of Physics

In investigating how science is practised and constructed in society, the sociology of science lays emphasis on its human and societal component, questioning its apparently 'mythical' status (Cunningham and Helms, 1998). The following discussion addresses sociological aspects of science (and implicitly Physics) and their subsequent implications for epistemology. In science studies these aspects are tackled at microsociological and macrosociological levels (Cunningham and Helms, 1998). The next sections dwell on these, as well as on the social patterns of interaction within the Physics community. Then, the combined implications of epistemology and sociology for pedagogy are explored in section 5.

4.1 Microsociological studies: scientific practice

Microsociological studies zoom in on the everyday practices of scientific production, offering depictions of the knowledge creation enterprise as it takes place in laboratory settings. They analyse how scientific undertakings and scientists' interactions and ways of working lead to the generation of scientific claims; how evidence is evaluated and negotiated in the scientific community; and how scientific knowledge gains validation and acceptance (Collins and Pinch, 1993; Gooding, 1990; Knorr-Cetina, 1995). Minute attention to the processes of knowledge creation has raised epistemological questions in relation to the unbiased nature of science and the supremacy of the scientific method in the production of irrefutable knowledge. Contradicting the objectivity of science, such studies have revealed the imprint of individual and cultural aspects and values on the process of knowledge production, justification, and its outcomes. Social aspects have thus become difficult to 'bypass' and epistemology has become intertwined with sociology (Tala, 2009).

For instance, studies have documented the disparity between the messy research process and the linear accounts of science presented in published material (Gooding, 1990; Wong and Hodson, 2009). These latter leave out or play down the 'messiness' of empirical work, concealing the extent to which scientists' accounts are 'reconstructions rather than records'. Reconstruction emerges as part and parcel of the scientific endeavour, whereby scientists 'iron the reticularities and convolutions out of thought (and action) to make a flat sheet on which a methodologically acceptable pattern can be printed' (Gooding, 1990, p.5). Similarly, according to a physicist's opinion in a study by Wong and Hodson (2009), the process and method of scientific investigation is flexible, chaotic, needing creativity and imagination in all the stages of an inquiry. The positivist appearance of scientific results thus contrasts with the less-positivist nature of scientific practice.

As to the evaluation of claims, analyses of scientific practices suggest that the consensus of the scientific community acts as enforcer of the validity of evidence and methodology (Cole, 1992; Tala, 2009; Wong and Hodson, 2010). Without a community structure, the justification process would result in 'endless regression' and no 'conclusive views' (Tala, 2009). However, there are different views on the extent of social manipulation: some claim that knowledge becomes authoritative through social institutional power, with the winner of the controversies invoking the idea of nature and imposing the rules of future research, while others merely acknowledge 'the rather indisputable fact that the scientific inquiry is a social process and the reasoned judgment is itself socially defined' (Tala, 2009, p. 279). Thus, according to positivism the rigour of the scientific method separates justified belief from mere opinion, whereas social studies of science point out the community consensus as the arbiter of justified belief.

4.2 Social interaction patterns and the pride-of-place of research

As a dimension related to the process of knowledge creation in Physics, physicists' social interaction patterns deserve attention too, especially because of their reflection (or lack of) in pedagogic practice, as discussed later on. It is argued here that the prime driver and moulder of social interactions in Physics is research as the practice which generates knowledge. Therefore, as a central component in physicists' activities, research assumes a 'pride-of-place' position.

Several studies identify the strong research orientation and the tight research organisation as defining features of Physics (Becher, 1990; Becher et al., 1994; Hermanowicz, 2006; Smeby, 1996, 1998, 2000). Research represents a critical element of physicists' career, capable of making the difference between success and failure, and steers their social behaviour. Therefore, the qualities which physicists consider essential for career success invariably revolve around research (Hermanowicz, 2006). Persistence emerges as a paramount quality, as physicists deal with rejection throughout their working life. Peer-reviews of papers and grant proposals often fail to yield results, as does the process of experimental and theoretical work (Hermanowicz, 2006). Smartness and civility, understood as collegiality which contributes to a work environment conducive to productive research, are other essential qualities for physicists. So is ruthlessness, related to the research endeavour and persistence, to 'picking time to work on things' and to publishing, since well-known physicists are famous 'because when a new idea comes out, they are quick about writing a paper on it, even if it's half-baked' (Hermanowicz, 2006, p. 143).

The tight research organisation and the 'ruthlessness' linked to research ambitions seem to result from the people-to-problem ratio and the urban character of Physics (Becher and Trowler, 2001, pp. 106-108). Making an analogy with ways of life, Becher and Trowler classify disciplines into urban and rural: narrow areas of study clustered around a few prominent topics, versus broad stretches of intellectual territory with vaguely delimitated problems and a variety of themes. In contrast to rural areas which display rather individual endeavours in settings with little interest overlap, in Physics teamwork, collaboration and competition are common social practices, essential to speed up knowledge generation, extend expertise and validate and reject claims (Wong and Hodson, 2010; Ford, 2008). The intense competition generates a concern with speedy publication (Becher, 1990; Becher and Trowler, 2001; Hermanowicz, 2006; Wong and Hodson, 2010). Associated with the indispensable interaction with colleagues and the desire to keep up-to-date are networking, the common circulation of articles before publication, and frequent participation in conferences (Becher, 1990). The pivotal role of research becomes evident again. It is through the medium of research that the apparent contradiction between ruthlessness and physicists' sociability could be explained. Both are necessary to the advancement of knowledge. Ruthlessness, applied to oneself and one's own time, enables progress in research and dissemination, but at the same time socialising and networking are indispensable to test ideas and get new insights.

The sports metaphors proposed by Kekäle (1999) are suggestive of the social relationships in urban and rural disciplines. In Physics the sense of collective concerns and collaboration prevails: it is like a fast team sport, researchers working together and competing intensely against other teams. In contrast, rural fields such as history are like jogging: people participate on their own or in small groups, the distance between start and finish is relatively long, the speed is low and there are many interesting paths to follow, so participants might not stay on the same track and reach the same destination (Kekäle, 1999, pp. 233-234).

4.3 Macrosociological studies: science and societal issues

Engagement with Physics and its disciplinary community is not experienced equally by all those involved (both existing and potential members), as testified by feminist critiques of science and postcolonial science studies. As examples of macrosociological studies, these tackle the relationship between science and society by investigating how issues such as power, politics, race, religion or gender interact with science. More specifically, such studies have: revealed the existence of barriers for certain social groups; looked into the causes of discrimination; and questioned conventional understandings of the nature of science.

A first type of studies have analysed the participation of women and ethnic minorities in science, highlighting the discrimination and stereotypes which these groups encounter in gaining equal access to science, in proving that they can do science, in gaining resources once they have become members of the scientific community, or in getting equal recognition for their acheivements (Blickenstaff, 2005; Carlone and Johnson, 2007; Etzkowitz et al., 2008; Harding, 1991; Nelson, 2007; Rosser, 2012; Tyson et al., 2006). Other studies have investigated the reasons for discrimination, i.e. the ethnocentric and androcentric nature of science which has led to the marginalisation of women and ethnic minorities. The gendered and white image of science (Harding, 2008; 2009) is revealed in Physics, too. An examination of the literature on gender and Physics pinpointed the generally unwelcoming workplace culture for women, inverting the source of concern from the 'problem of women in physics' to the 'problem of physics with women' (Götschel, 2011). Postcolonial science studies, in turn, have questioned the supremacy of white Western science, claiming the equal status and worth of indigenous knowledge systems (see, for example, Seth, 2009 on the special issue of *Postcolonial Studies 12* (4); Carter, 2008; Harding, 1998; Paty, 1999). On account of science being perceived as synonymous with the epistemologies and practices of the developed world, Western Science has been referred to as the 'ethnoscience' (Harding, 1998) which has subjugated other non-Western scientific and cultural traditions. Therefore, an inclusive and multicultural view of science is advocated which acknowledges local systems of knowledge – previously dismisses as unscientific – as attempts to make sense of the natural world in response to local needs (Carter, 2008; Harding, 2009).

Therefore, and of particular relevance here, macrosociological studies – both postcolonial, as above, and feminist (Mayberry et al., 2001; Subramanian, 2009) – have also challenged conventional understandings of the nature of science. They have raised epistemological questions about the nature of scientific knowledge, the way in which science is conducted and the fundamental assumptions upon which it is based. Feminist science studies, for instance, have engaged in a 'cultural deconstruction of science' (Bartsch, 2001) and recognized the interdependency of 'natures and cultures' (Mayberry et al., 2001). Questioning science's claims of neutrality, such writings suggest that there are no objectively knowable facts, arguing for an understanding of science as a socially and culturally determined set of practices. Feminist theories in Physics have also changed its image from 'an area of eternal truth and solid knowledge' to one of 'human endeavour and processes of solidification' (Götschel, 2011), as illustrated by Barad's (2007) theory of agential realism which acknowledges the entanglement of natures and cultures.

This section has dwelt briefly on sociological perspectives of science and Physics, both at micro-level as regards the production of scientific knowledge in the laboratory and at macro-level in the relationship between science and societal issues of gender and race. Of significance to this paper, such sociological insights have exposed epistemological foundations of the nature of science and Physics which challenge positivism. The relevance of sociological and epistemological characteristics for the pedagogy of Physics will be discussed next.

5. Pedagogy: Epistemological and sociological expressions

5.1 Epistemologies among educators and implications for pedagogy

A wealth of research has investigated the views about science held by educators (mostly at pre-university level) and students, in a variety of geographical contexts (Abd-El-Khalick, 2011; Abd-El-Khalick and Lederman, 2000; Belo, 2013; Iqbal et al., 2009; Lederman, 1992; Lee and Witz, 2009; Tsai, 2006; 2007). The findings of these studies suggest that science educators often adhere to a positivist epistemology, contrasting with the views on the nature of science promoted by science education organisations which have undergone a constant evolution (Abd-El-Khalick and Lederman, 2000). As explained by Abd-El-Khalick and Lederman (2000), during the early 1900s the nature of science was associated with 'The Scientific Method'. Then, while the 1960s still emphasised enquiry and procedural skills, in the 1970s scientific knowledge started to be viewed as tentative, subject to change, probabilistic rather than absolute, resulting from human endeavours to make sense of nature, particular to historical contexts, and empirical. In the 1980s, the role of human creativity in elaborating theories and the social dimension of science started to be acknowledged. The 1990s continued to emphasise the historical, tentative, empirical, and well-substantiated nature of scientific claims, as well as the interaction between personal, societal and cultural beliefs in the generation of scientific knowledge. However, in spite of these developments, a significant proportion of teachers still believed that scientific knowledge was not tentative or held a positivist, idealistic view of science (Lederman, 1992).

It is most likely a consequence of such views that knowledge transmission and students' systematic accumulation of factual information still appear to underpin to a large extent curricula and pedagogy in science in general and Physics in particular (Duschl and Osborne, 2002; Lattuca and Stark, 1994; Neumann, Perry and Becher, 2002; Smart and Ethington, 1995; Thacker, 2003; Wieman, 2007). Lattuca and Stark (1994) noted that, in hard fields, pedagogy at undergraduate level is characterised by 'curricular coherence' – also observed across undergraduate Physics programmes in Europe (Kehm and Eckhardt, 2009) – which means that students learn by building blocks of the discipline one upon another until reaching the prescribed level of understanding. In contrast, softer fields display curricular diversity and knowledge is usually acquired by recursive patterns of research rather than by systematic accretion, using multiple perspectives and pursuing knowledge in several directions simultaneously (Lattuca and Stark, 1994, p. 419). Similarly, an analysis of course content in various disciplines (Donald, 1983) revealed differences. In social sciences learning occurred around clusters of loosely-structured concepts where certain key ones acted as 'pivots' or 'organisers'. In contrast, Physics displayed hierarchical learning patterns with inter-linked, tightly-structured key concepts and with branches from more to less important concepts, suggesting an 'all-or-none learning pattern' (p. 37-38). The consequences of a highly prescriptive and tight curriculum, revealing a strong classification and framing (Bernstein, 1971) of undergraduate Physics, will be addressed in the remainder of this section.

5.2 Knowledge acquisition of 'ready-made science'

A perceived necessity of the 'all-or-none learning' of 'ready-made' scientific facts is probably what lies at the root of the emphasis on subject matter knowledge and on familiarity with 'the foundations of the scientific canon' (Duschl and Osborne, 2002). Nevertheless, pedagogic practices based on the assumption of a vast, orderly knowledge area which students are supposed to assimilate systematically contradict the process of knowledge creation in Physics, which was shown to involve messiness and collective and individual reconstruction. Positivist teaching approaches, in their varied manifestations, conceal the epistemic properties of scientific practice revealed by microsociological studies of science. Curricular material tends to hide the people and social contexts involved in the construction of science. Even when students are engaged in active scientific inquiry, there is often a push toward one right answer which promotes a singular vision of science (Barton and Yang, 2000). Thus, the image of the scientific process presented in science textbooks dismisses creativity as unnecessary, implying that dispassionate and systematic analysis of data will lead to secure conclusions (Wong and Hodson, 2009). In addition, classrooms are hierarchically structured, with the teacher and the text controlling which knowledge counts (Barton and Young, 2000; Cunningham and Helms, 1998; Duschl and Osborne, 2002), again indicative of the presence of strong framing and weak choices for students (Bernstein, 1971). Combined, such practices promote 'scientific concepts over scientific contexts' (Barton and Yang, 2000), engendering a vision of science as factual, decontextualized, linear, objective, rational, and uncontentious, where learning becomes equivalent to retention of information (Barton and Yang, 2000; Neumann, Perry and Becher, 2002). The emphasis lies on 'ready-made science' (with implicit messages about certain knowledge obtained through the scientific method), as opposed to 'science-in-the-making' which emphasises social construction (Wong and Hodson, 2010).

Moreover, students are confronted with an apparently neutral process of validation of empirical evidence in the form of 'the scientific method'. There is hardly any place for the 'awkward student' (Mody and Kaiser, 2008) who reaches the 'correct' answer via non-common sense methods, considers alternative interpretations and new ways of doing things, and thus constructs knowledge while learning. For example, in traditional introductory university Physics courses, laboratory activities usually consist of verifying principles that have been learned in lecture and completion of the laboratory simply requires following a set of rules to get to the end result. Students neither engage in discovery, nor practise laboratory skills necessary in research or in higher level courses (Thacker, 2003). Therefore, such practices hardly reflect the reality of physicists' day-to-day undertakings and the processes whereby claims are made, justified and validated through the consensus of the scientific community. Consequently, pedagogical methods centred on acquisition of certain, absolute knowledge, which neglect the process of knowledge production, fail to make students aware of key sociological aspects of the discipline and the ensuing epistemological implications related to how knowledge claims have come into being and achieved validation.

5.3 Student epistemology and conceptual understanding

Additionally, such pedagogical practices give students a false impression of the discipline: made up of facts about an objective reality, growing through neat, systematic accumulation of knowledge. This perception is not without consequences, since epistemological beliefs have been shown to influence student achievement (Hammer, 1994; Lising and Elby, 2005; May and Etkina, 2002; Ryder and Leach, 1999; Songer and Linn, 1991; Stathopoulou and Vosniadou, 2007). For example, Stathopoulou and Vosniadou (2007) found that if students see Physics knowledge as simple and/or certain they will focus on ‘piecemeal’ factual information to the detriment of conceptual understanding, since they will be likely to filter out tentative and controversial information which contradicts existing knowledge. In contrast, perceptions of Physics knowledge as complex, uncertain and evolving determine students to focus more on relationships and their change in time. Unsurprisingly then, pedagogic methods concerned with mere accumulation of factual knowledge have often been highlighted as counterproductive to deep learning and conceptual understanding of Physics (Bernhard, 2000; Duschl and Osborne, 2002; Ehrlich, 2001; Linder, 1992; Redish, 1999; Thacker, 2003; Wieman, 2007). One suggestion to counterbalance this negative effect entails the reduction of the cognitive load while at the same time helping students see the interconnections of taught concepts, which is expected to direct their reasoning away from ‘novice’ to ‘expert’ thinking (Wieman, 2007). As ‘novices’, they see Physics as isolated facts, unrelated to the world around them, which they learn by memorisation; on the contrary, as ‘experts’, they see Physics as a coherent structure of concepts that describe nature. When emphasising the learning of subject matter, instructors wrongly assume that expert-like ways of thinking will follow and students are therefore not helped to develop meta-cognition (Wieman, 2007). Therefore, one could presume the existence of a belief among instructors that, in order for students to develop conceptual understanding, all the knowledge imparted is necessary (manifest in the all-or-none learning pattern). However, such a cognitive overload can have the opposite effect. Additionally, two specific generic skills appear to be affected by the poor development of conceptual understanding: problem-solving and critical thinking.

5.4 Problem-solving and critical thinking

Problem-solving entails ‘hypothesis development and testing; use of mathematical modelling to describe and analyse the physical world; and awareness of issues of precision and rigour’ (Jones, 2009a, p. 181). Its centrality in Physics is uncontested and the development of problem-solving skills is integrated in teaching and practised in classroom and laboratory work (Jones, 2009a; 2009b; Redish, 1999; Thacker, 2003; Wieman, 2007). However, whether the way it is taught encourages conceptual understanding and deep learning is questionable. The importance of conceptual understanding – rendered by the concept of ‘knowledge structures’ – to problem-solving in Physics emerges from research which found that students with fragile knowledge structures and weak links between distinct parts may not be able to activate the knowledge necessary to solve a problem (Sabella and Redish, 2007). Yet, despite being the most important skill taught in the undergraduate years, problem-solving appears dominated by superficial mathematical calculations and fails to engage students in deeper analysis (Redish, 1999), suggesting mere memorisation of formulas. Similarly, some of the ‘top’ students with high scores on the quantitative problems were found to have very low scores on the conceptual part (Bernhard, 2000). Such findings suggest that although students do apparently develop problem-solving skills, this does not necessarily go hand in hand with the development of strong ‘knowledge structures’ and cognitive processes characteristic of expert physicists.

In addition, a tension is noted between the emphasis on content knowledge and generic skills such as critical thinking or communication, the latter overshadowed by the primacy of the former (Jones, 2009a). In order to cover what is perceived to be a vast knowledge domain, the early years in the study of Physics are dedicated to the teaching of physical concepts and principles deemed fundamental (i.e. factual information), whereas in social science or humanities personal opinion and critical thinking are integrated early on as fundamental skills to be cultivated (Jones, 2009a; Lattuca and Stark, 1994). A survey of European Physics bachelor programmes (Kehm and Eckhardt, 2009) revealed, nonetheless, that a large proportion (78%) integrated the acquisition of generic skills. The most commonly mentioned were English language skills (in non-English speaking countries), communication skills and project management skills, sometimes 'outsourced' to other departments or teaching and learning support centres (Kehm and Eckhardt, 2009, p. 16). While this might suggest an increasing concern with equipping students with abilities relevant to their rounded development and a future scientific career, it is worth noting, however, that the report does not mention critical thinking. Given its essential presence in a physicist's skills set, as discussed next, the question 'why' springs to mind.

Research points out that physicists generally recognise that evidence can only support theories and not provide definitive answers and absolute truths (Jones, 2009b; Schwartz and Lederman, 2008; Wong and Hodson, 2009; 2010). Scientists working at the research frontier do not know what the laws of nature are and can reach different solutions in trying to interpret these. Insufficient data leads to the co-existence of multiple theories and divergent views, with differences in interpretations eventually resolved by new evidence. Consequently, knowledge representations of the world undergo evolution (Latour, 2008) and much of what was accepted as true in the past is now believed to be wrong (Cole, 1992). In addition, creativity and imagination enter in the formulation of interpretations and theories (Wong and Hodson, 2009). These facts imply that uncertainty does belong in Physics and that critical thinking represents an indispensable skill for physicists faced with the relativism of knowledge. Yet, uncertainty is concealed by teaching approaches when these are based on positivist epistemologies. Students cannot easily embrace a critical attitude in a field with apparently uncontested knowledge and clear criteria for knowledge verification. This might explain why critical thinking is perceived as a challenge to teach in undergraduate Physics (Jones, 2009a). Even more worrying, students were found to hold more novice-like beliefs after having attended an introductory Physics course than before it (Wieman, 2007). One can only guess that it was the nature of the curriculum and pedagogical approaches, suggesting the certainty of knowledge and the objectivity of its methods, which was responsible for a shift towards novice thinking rather than expert thinking. Thus, in a feminist perspective on the Physics curriculum, Barad (1995) laments the 'acritical-anticritical' pedagogy embraced by the Physics community and argues for the teaching of the 'uncertainty principle'. Similarly, Feynman criticises teaching approaches which generally follow one path and induce students to believe in the validity and uniqueness of the 'fashionable' theory, rather than imparting to students a wide range of physical viewpoints:

> If every individual student follows the same current fashion in expressing and thinking about electrodynamics or field theory, then the variety of hypotheses being generated to understand strong interactions, say, is limited. Perhaps rightly so, for possibly the chance is high that the truth lies in the fashionable direction. But, on the off-chance that it is in another direction – a direction obvious from an unfashionable view of field theory – who will find it? (Feynman, 1965).

The realisation that there are multiple theories usually occurs at postgraduate level, once students start undertaking research and create new knowledge. Confronted with ambiguity, they develop critical thinking. Once again, a contradiction seems to emerge between physicists' practices, which involve constant searches and attempts to resolve uncertainties in order to make sense of nature, and the positivist teaching approaches which present knowledge as uncontested facts and fundamental truths, hardly promoting an inquisitive, critical attitude towards the imparted knowledge, essential in a physicist's skills repertoire.

5.5 Assessment

The emphasis on objective content knowledge also appears to influence student assessment, hence the distinction between assessment based on memorisation and application of course material in hard sciences, as opposed to assessment which requires analysis, synthesis of course content and critical thinking in soft sciences (Braxton, 1995). Physics students pass courses by remembering facts and problem-solving recipes (Ehrlich, 2001; Wieman, 2007), which favours an impression that Physics is effectively about memorization and use of formulas. Again, such assessment practices ignore uncertainty as a dimension of Physics epistemology and fail to develop students' critical inquiry abilities. Another noted tendency is that whereas hard sciences give more weight to final examinations, soft areas show a tendency towards continuous assessment (Neumann, 2001). However, the above-mentioned survey of Physics bachelor degrees (Kehm and Eckhardt, 2009) observed a change in the majority of continental European countries: a shift towards continuous assessment and a reduced emphasis on final summative exams described as the typical, traditional examination method in continental Europe (Kehm and Eckhardt, 2009; Tuning Project, 2008). Although the latter continue to have considerable weight, a recent concern with student-centred learning appears to have triggered a new practice: the assessment of learning outcomes after each module of unit of teaching (Kehm and Eckhardt, 2009, p. 15). A high majority of survey respondents (60%) also reported that in addition to knowledge their bachelor programmes assessed generic skills (Kehm and Eckhardt, 2009). Yet, these skills do not appear to include critical thinking. Therefore, assessment appears dominated by mastery of subject matter and mathematical formulas, failing to test students' development of capabilities indispensable to expert physicists.

5.6 Decontextualised science: effects on underrespresented groups

Besides the shortcomings identified so far, the image of science as objective, context-free and unitary conveyed by curricula and pedagogic practice has additional negative effects of alienation upon women and minority groups. As it promotes a Western and

gendered view of science (Harding 2008, 2009), underrepresented students find difficulty in relating to it, integrating it with their own contexts and finding meaning in science learning. Their identities clash with the culture of science, leading to low participation, problematic integration and frequent drop-out from science courses (Barton and Yang, 2000; Carlone, 2004; Carter and Smith, 2003; Jones et al., 2000; Kozoll and Osborne, 2004; McCullough, 2004; Miller et al., 2006). In Physics, a literature review on gender and education (Danielsson, 2009) revealed pedagogical implications such as the duality of the student body in terms of student identities, with male students interested in the discipline for its own sake and female students struggling to relate Physics, as it is taught, to their own reality.
Inspired by insights into the sociology of science, science education literature offers several suggestions about ways to make pedagogy more inclusive and relevant to women and underrepresented groups. A self-evident method refers to inclusive curricular material and textbooks which reflect gender and race diversity, through accounts of the contribution of scientists from underrepresented groups and of indigenous sciences to scientific knowledge (Barton and Yang, 2000; Brickhouse, 2001; Snively and Corsiglia, 2001;Whiteley, 1996). Other methods, however, could potentially benefit the student body as a whole, beyond assisting the integration of underrepresented groups. They generally target the strong framing of educational knowledge (Bernstein, 1971) in the direction of handing over to students more options and control over their learning. For example, under the influence of feminist epistemology, feminist pedagogies challenge power relationships in teaching between instructor, subject matter and students and promote instead a consideration of students' ideas and needs (Brickhouse, 2001). Such practices are likely to make science more attractive and engaging in general, while at the same time developing students' rounded scientific literacy. Concrete suggestions in this respect contemplate: consideration of students' prior experiences of science and their interests (Barton and Yang, 2000; McCullough, 2004); interactive environments that promote cooperation and discussion in the classroom (Lorenzo et al., 2006); teaching not only the ready-made products of science, but also knowledge about the processes of scientific production and the nature of science through engagement in activities which resemble scientists' practices (Cunningham and Helms, 1998; McGinn and Roth, 1999; Osborne, 2007). Additionally, such approaches could have an added benefit: they could raise students' awareness of the subjective dimensions of science, the collective processes of knowledge creation and evaluation of evidence, the co-existence of conflicting theories and the provisional character of knowledge, thus generating a more faithful alignment of pedagogy with the nature of knowledge and the process of knowledge production in Physics. This alignment in fact occurs at postgraduate level, as discussed next.

5.7 Research training: Pedagogy in tune

During research training at postgraduate level, instruction approaches finally seem to reflect the knowledge production and the social patterns of interaction characteristic of the Physics community. Students' initiation to research, part of their formal training in postgraduate studies, does not seem to display the inconsistencies observed in undergraduate education; instead, it appears to converge with the activities of expert physicists. The most likely explanation lies in the pride-of-place of research in the Physics profession discussed earlier. In a university environment, this translates into the fact that Physics academics identify themselves strongly with research, and less with teaching; and, as opposed to the arts and social sciences, they perceive supervision as research rather than teaching (Moses, 1990; Smeby, 1996; Becher and Trowler, 2001). They also spend large amounts of time on supervision, since students' work contributes to the department's research effort. Smeby (2000) found that at the University of Oslo supervision time fluctuated significantly: 42 hours per year in the humanities and social sciences, against 82 hours per year in the sciences.

Postgraduate students' integration in communities of practice (i.e. research groups) reflects the tight organisation of research and the urban nature of the discipline. Students work in a team alongside other students and staff which pursue similar research. They are often assigned topics directly associated with the supervisor's specialism (Becher, 1990; Smeby, 1998) and their work becomes part of the joint effort. In fact, Physics academics believe that it would be difficult to do research in universities without graduate students – hence the mutual dependency in the relationship between staff and students, beneficial for both parties. Students get involved in real research, and staff have a genuine interest in the topic and progress, as results will contribute to their own research (Smeby, 1998). A Physics academic describes students as a resource and their contribution as positive: 'they take part, solve problems and do a lot of hard work' (Smeby, 2000, p. 59). Students' socialisation into a community of practice is also evident in PhD students' perceptions of research in different disciplinary areas: whereas in medicine research is 'a job to do', in natural sciences and behavioural sciences students perceive research as a 'personal journey'. In natural sciences, this journey included learning how to be part of a research community (Stubb et al., 2012). Thus, since a career in Physics, within and beyond academia, is perceived to be intricately related to research, there is a pervasive concern among Physics academics to train students in research skills (Sin, 2012). While in soft and/or applied disciplines one could also claim research to be a defining characteristic for the academic profession, it is less likely to be required for graduates who leave academia for industry.

Therefore, one can conclude that through involvement with research, postgraduate students get acquainted both with the uncertainty inherent in Physics knowledge and with the complex process of knowledge creation and its social dimensions. It is only at postgraduate level –already a springboard to the Physics profession – that the tentative, socially-constructed nature of scientific knowledge becomes obvious, testifying to a more faithful alignment between disciplinary epistemology, sociology and pedagogy.

6. Discussion and implications for pedagogic practice

The paper set out to analyse the relationship between epistemology, sociology and pedagogy in Physics and has offered some examples of learning and teaching approaches and practices which illustrate (mis)alignment with disciplinary epistemology and sociology. In so doing, it has raised questions about the disciplinary essentialism embodied in positivist epistemologies, warning that the assumption of the presence of some quintessential properties of Physics (objective, logic, context-free, uncontroversial, etc.) can condition pedagogic practice in a way which is detrimental to students' understanding of the discipline, their learning and their development. With such an insight, the paper casts doubt on the continuing authority of Becher and Trowler's (2001) characterisation of hard-pure areas and, by extension, their clear-cut disciplinary classification which has informed much subsequent pedagogic research.

Coming back to the theoretical concepts of classification and framing (Bernstein, 1971), a dividing line becomes evident between undergraduate and graduate pedagogy. *Undergraduate teaching* appears to rely on a *strong classification* – clear knowledge boundaries which contain the *core Physics knowledge* – and, deriving from it, to display a *strong framing* whereby instructors' and students' options with regards to selection, organisation and transmission of knowledge is limited. Strong classification and framing translate into a *tightly-bound curriculum* which displays resemblance across countries (Kehm and Eckhardt, 2009), suggesting the *universal and context-free* character of Physics knowledge. The emphasis on the acquisition of this knowledge betrays a concern with *ready-made science*, that is, with *the outputs of the scientific process* of knowledge creation. On the contrary, *postgraduate education* appears to be characterised by weak classification and weak framing. *Weak classification* reflects the *lack of consensus over frontier knowledge* and students, through research, get introduced to the *uncertainty* inherent in treading this knowledge territory. *Weak framing* is manifest in the range of choices available to students, since they have reached a level which entails *specialisation* and decisions about research avenues worth pursuing. The preoccupation now lies in students' induction to authentic scientific practices of knowledge creation and validation through their integration in a research community, as well as in their socialisation into the interaction patterns characteristic of the discipline. The emphasis is no longer on the output of the scientific process, but on *the scientific process itself*, or on *science-in-the-making*. Undergraduate education thus appears to embrace a positivist epistemology, whereas postgraduate education a relativist, social-constructivist one. It is the latter which is supported by evidence from research in science studies and by the history, philosophy and sociology of science, which suggest that the nature of scientific knowledge and the process of knowing are tentative, situated in a social and historical context, a result of individual and collective endeavours.

One can therefore argue that the strong classification and strong framing which characterise Physics curricular knowledge and teaching at undergraduate level are a consequence of an underpinning positivist epistemology. Despite Physics knowledge being documented to advance through radical shifts and disciplinary revolutions, its teaching appears to be characterised by tight organisation, systematic assimilation of knowledge and the 'all-or-none learning pattern' (Donald, 1983). Additionally, the emphasis on content knowledge hides from students the process of knowledge creation and its human and social dimension. Therefore, these pedagogic approaches give an impression of neat growth of the discipline, logic and objectivity, leading to students' adoption of a positivist epistemology, which has been shown to affect their conceptual development. Moreover, the concern with subject matter and the acquisition of what is portrayed as objective knowledge and facts appear to overlook the uncertainty principle in Physics whereby its knowledge corpus consists not of absolute truths, but of theories. Critical thinking, which as a result would appear a paramount skill for a physicist, is hardly contemplated in undergraduate curricula, becoming overshadowed by content knowledge (Jones, 2009a; 2009b; Lattuca and Stark, 1994). Consequently, one could argue that teaching approaches based on strong classification and strong framing, driven by a reliance on apparently uncontested and universal knowledge to be assimilated systematically, fail to reflect the social-constructivist epistemology manifest in expert physicists' ways of working. They also fail to give students a holistic view of Physics, to include science-in-the-making in addition to ready-made science, and hinder the development of key attributes such as critical thinking, conceptual development, and the ability to tackle problems from multiple perspectives.

How could these two dimensions be reconciled? Referring to the false dichotomy 'constructivism versus content', Redish (1999) argues that it is important for students to learn both the process of science and the content, which can be achieved through an approach he calls 'scientific constructivism'. This entails designing learning environments which favour students to construct correct scientific ideas through tightly guided discovery, while at the same time covering the subject matter. While it seems taken-for-granted that students need to learn about the fundamental physical concepts and laws (i.e. the body of knowledge), the appearance of absolute objectivity could be counterbalanced by bringing science and technology studies in the classroom (Mody and Kaiser, 2008), as well as by introducing students to the history and philosophy of science (Matthews, 1994; Fensham et al., 1995). Extending the science curriculum to integrate these components, students can become aware of how physicists work, of the struggles involved in elaborating theories, of controversies, the 'winners' and 'losers' among competing theories, and of the fact that knowledge verification and validation contain, too, a human dimension and occur in a specific laboratory, in a specific place and time; in sum, that theories can, therefore, be prone to error. Making students aware of these facts is one step towards making space for 'the awkward student' (Mody and Kaiser, 2008) and towards developing students' critical thinking and conceptual understanding.

Consistency between the epistemology, sociology and pedagogy of Physics has been noted primarily in practices associated with postgraduate level teaching, characterised by weak classification and framing. The pronounced research preoccupation in Physics is reflected in pedagogic approaches. Student supervision is perceived as research rather than teaching, students are integrated in departmental research efforts and their research is usually closely related to supervisors' specialism. Critical thinking, an essential skill in research, appears to be cultivated in postgraduate students. The 'group-based apprenticeship model', contributing significantly to students' socialisation into the discipline (Neumann, 2001), mirrors the high level of teamwork encountered in urban disciplines and the collective process of science-making. Pedagogic practices at postgraduate level, driven by students' induction to research, thus seem a faithful reflection of physicists' working environments. A stronger presence of research in the undergraduate curriculum, already advocated in the science education reform literature, could therefore represent another means of narrowing the gap between disciplinary epistemology, sociology and pedagogy.

7. Concluding remarks

Two overall recommendations emerge from this paper: the explicit contemplation of disciplinary epistemology in teaching, while avoiding the dangers of epistemological essentialism; and the contemplation of the epistemological dimension in pedagogic research.

Students new to a discipline are unaware of the nature of its knowledge, its structure, and the methods involved in its creation, verification and justification. In the absence of this epistemological foundation, teaching approaches can give students incomplete or inaccurate impressions about a discipline. Natural sciences could thus appear consensual, impersonal and value-free, neglecting the social or philosophical factors at play. Social sciences, on the contrary, might appear to students as overly divergent, individual and subjective. Cole's (1983) findings refute these common misconceptions, highlighting that 'in the natural sciences, there is probably less consensus at the frontier than has been assumed and that, in the social sciences, there is probably more consensus at the frontier than has been assumed' (p. 134). It therefore emerges as paramount to include in the teaching of a discipline accounts and insights about its history and evolution, the competing theories and the surviving ones, i.e. how it has arrived at its present corpus of knowledge, so as to give students a holistic understanding of their field of study. It also emerges as paramount to familiarise students, already at undergraduate level, with the practices of knowledge production and validation common in their discipline's community.

These findings also make a case for the contemplation of the disciplinary epistemological dimension in research on teaching and learning, which has often been generic. Epistemological considerations can bring to light nuances able to enrich our understanding of pedagogic approaches across disciplines. These could also contribute to building bridges and facilitating understanding between different disciplinary areas, especially given the increasing interdisciplinarity in higher education and the need for academics in different areas to find common grounds for practice. Therefore, having analysed the relationship between disciplinary epistemology, sociology and pedagogic approaches in Physics, the paper could be seen as an attempt to shed light onto pedagogic idiosyncrasies and increase transparency for other disciplinary communities.

This paper has offered only a bird's-eye-view of the relationship between epistemology, sociology and pedagogy. Further research could investigate in more depth specific pedagogic aspects or methods in which the social and epistemic interact in Physics education. Moreover, the paper acknowledges epistemology to be but one likely influence on academic practice. Therefore, another path for further research could explore the complexity of the reasons behind disciplinary pedagogic approaches, considering not only their epistemological characteristics, but also context-dependent social determinants, departmental cultures and individual factors.

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