From threshold concepts to transformative learning: Cognitivist perspectives on how philosophy could enrich physics teaching

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Abstract

Calling into question the current predominant assertion that physics is best taught without recourse to metaphysics, I investigate how an attention to philosophy of science can improve student learning. An analysis of the historical development of physics within the framework of Kuhn's scientific revolutions suggests that (i) philosophical debate could lead students to a deeper understanding of physics paradigms and (ii) an awareness and acceptance of a multitude of philosophical positions could enable them to generate truly novel research. These two claims are substantiated by a cognitivist analysis which draws on the ideas of threshold concepts and transformative learning, respectively. The possible implications of these ideas for university physics teaching are explored by comparison with results from implementing philosophy-based teaching in high school physics.

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1 Introduction

My primary motivation for studying physics was the wish *'[to] know what makes the world revolve, [i]ts inner mysteries resolve'* (Von Goethe & Williams 1999, p. 383). I naturally assumed that philosophy of science would have to be an integral part of such an endeavour. However, during my undergraduate studies at the University of Cologne, I encountered a physics curriculum that was complemented by electives from mathematics, chemistry, computer science, biology, geophysics and meteorology (University of Cologne 2013), but made no reference to philosophy. I later came to learn that this was not a mere oversight: Many of my teachers held that pondering too much over philosophical issues can hinder progress in physics learning. This is symptomatic of a widespread attitude amongst practising physicists as summarised by the bon mot *'Shut up and calculate!'* (Mermin 2004, p. 10).

In my opinion, the banning of philosophical aspects from the governing teaching practice presents a serious limitation of physics learning. To support this perception, I intend to discuss whether and how an attention to philosophy of science may indeed enhance the learning experience. Aiming at enriching and complementing current teaching rather than radically altering it, I will attempt to both construct a persuasive argument in favour of including philosophy in the physics curriculum and to sketch the possible consequences of such an approach. The analysis will refer to the whole academic learning trajectory of physics students from undergraduate to postgraduate stages (Buhmann 2012) and, in particular, beyond.

As my central question revolves around the linking of two highly nontrivial subject matters, physics and philosophy, I will assume a cognitivist perspective (Woolfolk, Hughes & Walkup 2012) which is *'oriented towards the classic topic of the learning content'* (Illeris 2009, p. 4). Consciously limiting the scope and scale of my discussion, I will thus focus on an individual's attempts at understanding and largely ignore the social aspects of learning (Tennant 2006). The possible impact of philosophy on understanding physics is a complex learning phenomenon which prohibits an analysis in terms of an information-processing model of cognition (Anderson 2010), let alone a neuroscientific account (Goswami 2004). Instead, its defining aspects are best revealed by invoking advanced educational ideas such as threshold concepts (Meyer & Land 2003) and transformative learning (Mezirow 2009).

My argument will unfold as follows. A close inspection of Kuhn's (2012) account of the history of science will show that philosophical considerations have played a crucial role in research leading to the current-day body of physics knowledge. I will conclude that (i) a likewise attention to philosophy during physics learning can foster a deeper understanding of central results and speculate that (ii) open-ended philosophical debate could prepare students for a future role in advancing this knowledge (Sect. 2). Further evidence to claim (i) is added by exploring the striking parallels between paradigm shifts (which play a pivotal role within Kuhn's historical account of research) and threshold concepts (which have a similarly central function within learning). I will investigate whether philosophy of science can be understood as an aid for successful threshold navigation (Sect. 3). A different educational angle will support claim (ii) and suggest that the impact of philosophy of science might be even more profound. I will argue that acquiring philosophical metacognition can be viewed as an instance of transformative learning (Sect. 4). Finally, I will attempt to outline the potential impact of philosophy of science on physics learners, teachers and the way we organise physics learning (Sect. 5).

2 The impact of philosophy: from physics research to physics learning

The intended endpoint of university education in physics is the independent researcher. Conversely, the results of past research feed into the content of current physics learning. This mutual interdependence provides the rationale for my choice to begin the investigation of the possible relevance of philosophy to physics learning by discussing the already established role it plays in physics research.

Insights into the structure and evolution of physics research can be obtained from historical approaches to philosophy of science which place an *'emphasis on the practice of science in its historical development'* (Carrier 2012, p. 132). Most of them advocate a very uniform, cumulative view of scientific progress. Popper's falsificationalism paints a picture of scientific theory-generation as a quasi-continuous process of gradual knowledge extension whereby *'a [new] theory replaces a refuted predecessor, … the successor approximately preserv[ing] the earlier account if the circumstances are suitably restricted'* (Carrier 2012, p. 132). Similarly, Lakatos's descriptive account of research programmes holds that *'[a]n acceptable successor … is required … to account for all those phenomena that are successfully explained by its predecessor'* (Carrier 2012, p. 140). Kuhn (2012) developed his distinctly dynamical account in opposition to such cumulative views. In the words of Hacking (2012), he has replaced Popper as the *'most influential philosopher of science—I mean the most widely read, and to some extent believed, by practicing scientists'* (p. xiv). This wide acceptance aside, I have chosen to base my investigation on Kuhn's theory, because it displays the richest structure among all historical approaches and because he explicitly provides a place for metaphysics within this structure.

Let me begin by outlining the main elements of Kuhn's (2012) model of scientific progress. In stark contrast to the quasi-continuous models of gradual knowledge accumulation, he postulates that scientific practice exhibits two very distinct modi operandi. Normal science is characterised by an allegiance to a predominant paradigm. Following Kuhn's later refinement, I understand the notion paradigm in a global sense as a *'disciplinary matrix'* (Kuhn 2012, p. 181) comprised of *'symbolic generalizations'* (Kuhn 2012, p. 182), i.e., laws of nature and their interpretation; *'metaphysical'* (Kuhn 2012, p. 183) beliefs ranging from heuristic to ontological; *'values'* (Kuhn 2012, p. 184) for judging predictions and theories; and *'exemplars'* (Kuhn 2012, p. 186) of problems and their solutions. This complex concept of a paradigm exhibits a rich internal structure and provides a framework for discussing the central constituent elements of any major physical theory. It is in contrast to the alternative, more local and literal meaning of a paradigm as just an exemplar for problem solving. Normal science is *'a highly cumulative enterprise, … the steady extension of scientific knowledge'* (Kuhn 2012, p. 52), whereby *'the paradigm forces scientists to investigate some part of nature in a detail that would otherwise be unimaginable'* (Kuhn 2012, p. 25). However, it does not *'aim to produce novelty, conceptual or phenomenal'* (Kuhn 2012, p. 35). In my understanding, normal science takes place within the relatively safe confines of a paradigm, undisturbed by existential doubts about the founding elements of the reigning theory. This limitation frees capacity for scientists allowing them to perform technically very elaborate research, but ultimately prohibits them from making very deep, fundamental progress.

Really profound and novel findings are reserved to the complementary modus operandi, extraordinary research, which is marked by *'the proliferation of competing articulations, the willingness to try anything, the expression of explicit discontent, the recourse to philosophy and to debate over fundamentals'* (Kuhn 2012, p. 91). It is triggered by anomalies which have to have *'lasted so long and penetrated so deep that* *one can appropriately describe the fields affected by [them] as in a state of growing crisis'* (Kuhn 2012, p. 68). Extraordinary research in response to crisis may lead to a *'transition to a new paradigm [which] is [a] scientific revolution'* (Kuhn 2012, p. 90): *'a reconstruction of the field from new fundamentals'* (Kuhn 2012, p. 85). As a result, *'the scientist's world is qualitatively transformed as well as quantitatively enriched by fundamental novelties of either fact or theory'* (Kuhn 2012, p. 7). To summarise in my own words, extraordinary scientists ask exactly those fundamental questions that normal scientists shy away from. This very painful process which involves leaving behind treasured beliefs reaps a high reward: a new and better understanding of some aspects of the physical world.

Attempting to judge the plausibility of Kuhn's two-phase model from my own limited, but inside perspective as a practising (normal) scientist, I can assert that his description of normal science in its practice closely matches my experience. Not having witnessed the unfolding of a scientific revolution first-hand, I have to rely on textbooks, which, as Kuhn (2012) warns, *'inevitably disguise not only the role but the very existence of ... scientific revolutions'* (p. 137). Nevertheless, my textbook-informed image of the development of physical theories is very compatible with Kuhn's model of extraordinary science, which indicates how convincing his theory is. In my opinion, its essence and main achievement is the identification of the deep internal conflict inherent in scientific activity: that between the need to operate on the basis of a solid foundation on the one hand and the inevitable eventual requirement to abandon this basis in order to achieve profound progress on the other. Metaphorically speaking, the scientist is regularly faced with the challenge to bite the hand that feeds him.

Having thus introduced Kuhn's theory as a rich framework for interpreting the historical development of science and its inherent struggles, I can turn to the role he assigns to philosophy. Recall that Kuhn explicitly names metaphysical beliefs as one of the four pillars constituting a paradigm. Philosophical assumptions become particularly relevant during phases of extraordinary science where their critical examination facilitates the generation of fundamental new concepts and ideas:

> *'It is, I think, particularly in periods of acknowledged crisis that scientists have turned to philosophical analysis for unlocking the riddles of their field. ... It is no accident that [scientific revolutions] have been both preceded and accompanied by fundamental philosophical analyses of the contemporary research tradition.'* (Kuhn 2012, p. 88)

This view is shared by the natural scientist and historian of philosophy Scheibe (2006) who has studied the philosophical views of leading physicists. He identifies 36 physicists as actively concerned with with philosophical questions. A comparison quickly reveals that the majority of the listed scientists were responsible for those scientific revolutions explicitly mentioned by Kuhn in his examples. Asking the question why these physicists turned philosopher, he concludes: *'Philosophising physicists appear whenever physics becomes interesting and "too hard for the physicists" '* (Translated from German, p. 11). Note that while both Kuhn and Scheibe advocate philosophy as a tool for physics, Weinert (2004) has investigated the reverse influence of new physical theories on philosophy.

Philosophy as an aid for teaching normal science

A historical perspective on theory-development has thus revealed that crucial, breakthrough progress has typical been made during scientific revolutions and that these are signified and made possible by a close attention to philosophy. What implications does this observation have for physics teaching? One possible answer can be developed from Kuhn's (2012) own analysis. He claims that teaching in the natural sciences is dominantly mediated by *'textbooks, ... being pedagogic vehicles for the perpetuation of normal science'* (p. 136). *'[T]hey aim quickly to acquaint the student with what the contemporary scientific community thinks it knows'* (Kuhn 2012, p. 137), in other words, the current predominant paradigms. I can confirm this tendency, which is partly driven by the need to convey a wealth of interrelated concepts and ideas in a very tight curriculum, from my own experience as both learner and teacher of physics. Kuhn's characterisation is particularly true for undergraduate teaching of subjects which are *'considered 'dead', classical material'* (Nespor 1994, p. 60).

Attempting to identify the four components of a paradigm as a disciplinary matrix within a typical undergraduate physics textbook, I observe that symbolic generalizations and exemplars are explicitly taught, while values and metaphysical assumptions are not usually discussed in textbooks or indeed, in any other part of the physics curriculum. A possible reason for this omission can be found in Kuhn's (2012) claim that *'the existence of a paradigm need not imply that a full set of rules exists'* (p. 44) and his conclusion that they may be a part of tacit knowledge as introduced by Polanyi (1966). However, Sternberg & Horvath (1999) have argued that *'tacit knowledge is important to success'* (p. 232) and that *'[it] can become explicit'* (Sternberg & Horvath 1999, p. 232). To summarise, physics teaching as envisaged by Kuhn aims at conveying the governing paradigms to normal scientists in the making. However, it fails to address the philosophical assumptions which form an integral part of these paradigms, in spite of the apparent possibility to make such tacit knowledge explicit. I conclude that Kuhn's physics teaching is ineffective and must fall short of reaching its proclaimed goals.

An attention to philosophy may hence be advocated as a means to making normal-science teaching more complete and effective. This claim can be supported by unpacking the notion of physics practice, where I assume a cognitivist point of view. In particular in theoretical physics, practice is a predominantly cognitive endeavour which involves the manipulation of theories, abstract concepts and formulas. The object of study is often intangible and can, even experimentally, only be experienced in an indirect form as mediated by the interpretation of meter readings via elaborate observational theories. As a consequence, practice in physics research is very different from the much more concrete practices in the vocational professions whose observation inspired Lave & Wenger's (1991) communities of practice concept. In physics teaching, there is an even more pronounced lack of concrete sensual experience: The large body of abstract concepts cannot exhaustively be supported by experimental demonstrations. In addition, cutting-edge experiments are typically too elaborate to be shown to a large student audience. This lack of directly observable practice can partly be compensated by cognitive practice in the form of a thought experiment, which according to Sorensen's (1992) definition *'is an experiment that purports to achieve its aim without benefit of execution'* (p. 205). Kuhn (2012) mentions thought experiments alongside philosophical analysis as a means to establishing new paradigms: *'Nor is it an accident that … thought experiments should have played so critical a role in the progress of research'* (p. 88).

These two interrelated analytical devices, philosophy and thought experiments, which have played a decisive role in the establishment of paradigms, can thus facilitate their acquisition and internalisation by students. Their role can be conceptualised as fostering a deep approach to learning. They simultaneously serve the function of no less than three of Entwistle's (2009) six *'critical features of teaching that encourage a deep approach and integrative personal understanding'* (p. 125), namely, they encourage discussion, emphasise critical features and exemplify critical thinking. In particular, philosophical discussions provide a wider context for physical theories and may help create new connections between seemingly unrelated ideas within a paradigm. They may be viewed as fostering metacognitive awareness in the limited sense of making the narrow framework of desired metaphysical beliefs explicit, i.e., those which are related to the paradigm to be taught.

Furthermore, philosophy and thought experiments may be viewed as additional and alternative pedagogical vehicles. As Gardner (2009) concludes from his theory multiple intelligences, they could open the *'possibility of reaching more students in more effective ways'* (p. 107) by *'fostering multiple representations'* (p. 113). Amongst the range of methods at the disposal of the teacher, philosophical discussion stands out because of its diagnostic power to reveal student misconceptions. One might object that the addition of yet another theoretical tool such as philosophy further increases the apparent imbalance to the disadvantage of practice in the concrete sense of the word. However, an insistence on the latter is not adequate for theoretical physics, because it fails to acknowledge the largely cognitive nature of practice as imposed by the abstract subject matter.

Philosophy for facilitating extraordinary science?

The above rationalisations how philosophy can improve physics learning are all compatible with Kuhn's understanding of teaching as a means to promote normal science. A radically different idea of what philosophy might contribute can be arrived at by adopting a more critical stance towards Kuhn's model. In particular, I am doubtful of his interpretation of normal science and his very static and categorical distinction of normal vs extraordinary science. His claim that in spite of their *'desire to be useful, [their] excitement of exploring new territory, [their] hope of finding order, and [their] drive to test established knowledge'* (Kuhn 2012, pp. 37–38), normal scientists are *'almost never doing any of these things'* (Kuhn

2012, p. 38) seems to point towards a highly implausible mass delusion. When Kuhn (2012) speaks of a *'transition from normal to extraordinary research'* (p. 91) rather than individuals' transitions from normal to extraordinary researchers, he underplays the desire and potential of normal scientists to be a part of scientific revolutions. My reservations seem in resonance with Popper's (1970) who writes that *'the 'normal' scientist, as Kuhn describes him, is a person one ought to be sorry for ... [and who] has been taught badly'* (p. 52). Going even further, Feyerabend (1970) accuses Kuhn's *'emphasi[s] [of] the dogmatic, authoritarian, and narrow-minded features of normal science'* (p. 205) of being *'incompatible with a humanitarian outlook'* (p. 210). Maybe a view of teaching as a very focussed and goal-oriented activity towards the forming of normal scientists is too narrow.

Indeed, Kuhn's restriction of teaching to the realm of normal science begs the question: Who teaches the extraordinary scientist? Kuhn (2012) seems to think that extraordinary science is not or maybe cannot be taught. Instead, *'[a]lmost always the men who achieve these fundamental inventions of a new paradigm have been very young or very new to the field whose paradigm they change'* (p. 90). However, as Kuhn himself concedes in his above characterisation of normal scientists, they do strive to explore new territory and test established knowledge. In other words, every normal scientist wants to be an extraordinary scientist. If at all possible, physics teaching should therefore assist students in moving towards this ideal.

Extraordinary science can be encouraged in students by teaching them exactly those cognitive tools used by extraordinary scientists in times of crisis, i.e., a willingness to try out a variety of new and competing ideas and a recourse to philosophical debate. Such a mode of working is very creative. Howard-Jones (2008) has proposed that creative thinking can be characterised *'as an alternation between two very different modes of thinking, described here as generative and analytical'* (p. 8). Supporting this claim from a neuroscientific perspective, Howard-Jones et al. (2005) stress that associations play an important role in creativity. Philosophical debates can contribute to the fostering of creative thinking if they aim at challenging established views and opening up a variety of new perspectives. The teaching of philosophy to this end cannot be constrained to the narrow confines of those philosophical perspectives underlying the current predominant physics paradigms. Instead, also the philosophical positions underlying outdated paradigms; the ones considered, but ultimately not adopted during scientific revolutions; and even those which seem to have no immediate influence on physical theories have to be introduced. As a result, one may expect to inspire in the students a genuine metacognitive awareness which includes a critical reflection of the metaphysical assumptions underlying their own reasoning in physics and an appreciation of the available alternatives.

An additional and immediate lesson from Kuhn's analysis is the fact that scientific progress requires, at least from time to time, a readiness for radical theory-change. Students can only hope to become extraordinary scientists if they display a readiness and willingness for such change. This readiness can be instilled by a historical approach to teaching which conveys the message that the body of physics knowledge has been and will be subject to change and that this process can be a painful struggle. Student feedback at Imperial College indicates that learners appreciate such an attention to history in physics teaching (Humphris 2012).

To conclude, teaching based on history and philosophy of science (Teixeira, Greca & Freire Jr 2012) can and should foster a multitude of philosophical ideas and perspectives and a willingness by the students to question their espoused beliefs. In this way, it may help enable students to one day become extraordinary scientists.

Somewhat ironically, I have shown that philosophy of science may be read as a strong advocate for its own inclusion in physics learning. Kuhn's (2012) historical approach to philosophy of science gives evidence that ground-breaking developments in research have typically been accompanied and even facilitated by a close attention to philosophical questions. Drawing on Kuhn's own account of physics teaching on the one hand and his critics' views on the other, I have developed two very different theses on how philosophy could improve physics teaching. (i) *Philosophy for normal science:* I have concluded that a deep understanding of ruling physics paradigms can be encouraged by an appreciation of just those philosophical considerations that helped first conceiving them. (ii) *Philosophy for extraordinary science:* I have speculated that multi-faceted and open-ended philosophical debates could foster those abilities in students that might enable them to be part of scientific revolutions.

In the next two sections, I will attempt to place both of these theses on a firmer education-theoretic footing by employing the frameworks of threshold concepts and transformative learning, respectively.

3 Threshold concepts: philosophy of science as a vehicle for successful passage

As argued by Kuhn (2012), the acceptance of a new paradigm marks important non-cumulative progress made by researchers. Which phenomenon might be viewed as mirroring such progress on the side of the learner? I propose threshold concepts as a pedagogical framework which exhibits striking parallels with Kuhn's model of scientific evolution. I will begin by introducing threshold concepts and comparing them with Kuhnian paradigms and then employ the framework to illuminate the potential role of philosophy of science in assisting the navigation through threshold concepts.

A threshold concept was originally described by Meyer & Land (2003) as

> *'akin to a portal, opening up a new and previously inaccessible way of thinking about something. It represents a transformed way of understanding, or interpreting, or viewing something without which the learner cannot progress.'* (p. 1)

As defining characteristics, they suggested that threshold concepts

> *'may be transformative (occasioning a significant shift in the perception of a subject), irreversible (unlikely to be forgotten, or unlearned only through considerable effort), and integrative (exposing the previously hidden interrelatedness of something). In addition they may also be troublesome.'* (Meyer & Land 2005, p. 373–374)

Finally, it was suggested that they may be *'bounded, possessing terminal frontiers, bordering with thresholds into new conceptual spaces'* (Meyer & Land 2005, p. 374). The authors have further elaborated their framework by drawing implications for curriculum design (Land, Cousin, Meyer & Davies 2005), diagnosis and assessment (Meyer & Land 2010) and identifying variation in learners' responses to threshold concepts (Meyer, Land & Davies 2008). More recently, the focus has shifted towards the dynamics of the passage through the threshold. Elaborating on Meyer & Land's (2005) earlier, ethnography-inspired concept of a liminal state, Land, Meyer & Baillie (2010) have identified preliminal, liminal and postliminal stages of threshold-concept navigation, which they have characterised as instigative, reconstitutive and consequential, respectively.

There have been attempts to establish a more rigorous formal basis for threshold concepts from a multitude of perspectives. Mead & Gray (2010) have tried to formalise their structure within a framework of Disciplinary Concept Graphs. In an alternative structural analysis, Davies & Mangan (2010) discriminate threshold concepts from basic concepts where *'the full significance of a basic concept is only grasped once a transforming threshold concept has been subsequently incorporated into a learner's thinking'* (p. 195). Using methods from cognitive psychology, Weil & Mcguigan (2010) have proposed a distinction between genuine threshold concepts and threshold conceptions, with the latter referring to skills rather than concepts. Focussing on the learning dynamics, Schwartzmann (2010) has attempted to give a discipline-independent account of threshold concepts in terms of rupture of knowing with resulting defensive vs reflective student responses.

Following this brief introduction, I will next attempt to link threshold concepts to paradigms via striking structural resemblances and the core metaphor underlying paradigm shifts. Beginning with the structural analysis, I observe that paradigms exhibit all the defining characteristics of a threshold concept. The transformative nature of paradigm shifts is most strikingly confirmed by the fact that the authors even employ identical metaphors to describe the effect of the transformation, compare *'paradigm changes do cause scientists to see the world of their research-engagement differently'* (Kuhn 2012, p. 111) with *'a threshold concept ... represent[s] 'seeing things in a new way' '* (Meyer & Land 2003, p. 1). The irreversibility of paradigm shifts is captured by Kuhn's (2012) notion of the incommensurability of a new paradigm with its predecessor. Paradigms are integrative by definition, in stark contrast to pre-paradigm theories which *'juxtapose facts ... that will for some time remain to complex to be integrated with theory at all.'* (Kuhn 2012, p. 16). Troublesomeness is implicit in the crisis which the perceived failure of a current paradigm evokes. Finally, the boundedness of obsolete paradigms extends to current paradigms by historical extrapolation.

Some structural resemblance is apparent also in the dynamics of threshold navigation/paradigm shifting. The preliminal, liminal and postliminal stages of the former may be loosely linked with the phases crisis, scientific revolution and resolution of a revolution in Kuhn's (2012) framework. Note that while the transition in both frameworks can be either very sudden or extended over a considerable amount of time, a certain element of discontinuity is required in both cases. However, the dynamical structure also reveals an important difference between paradigms and threshold concepts: The learning of a threshold concept is a journey with a well-defined end and teachers who can guide the way towards this end. Before the establishment of a new paradigm on the contrary, it is not even clear whether such a paradigm as the goal of the scientist's struggle exists and what it might look like. These differences can be mitigated by adopting an cognitivist point of view: From my own experience as a researcher I can assert that the solving of a problem is driven by the firm belief in the existence of a solution and that the internal sensations following successful learning and research are very much alike.

A second, more associative connection between threshold concepts and paradigms can be drawn via the revolutionary metaphor. Kuhn (2012) justifies the use of this core metaphor by carefully demonstrating the similarities of paradigm shifts with political revolutions. One the other hand and rather revealingly, a real political revolution, The Singing Revolution in Estonia and its effects on the learning society have been conceptualised by Kutsar & Kärner (2010) in terms of a threshold concept. The metaphor of revolution reveals that a paradigm shift is qualitatively more than a threshold concept. While the navigation through a threshold concept is primarily an internal phenomenon of a student's cognition, the establishment of a new paradigm involves not only its construction, but also its negotiation and acceptance, which is a social phenomenon. However, the revolutionary metaphor should not be taken to literally. The struggles and sociological transformations within a scientific community during a paradigm shift are akin to those of a political revolution, but they do not automatically involve social and cultural transformations. Indeed, as Hacking (2012) points out, *'Kuhn [is] not talking about <u>the</u> scientific revolution'* (Original emphasis, p. xiii) which explicitly bears the traits of social change.

Finally, a common feature of Kuhn's (2012) and Meyer & Land's (2003) theories is their popularity and broad applicability. While appeals to paradigms and paradigm shift are used almost inflationarily in public discourse, threshold concepts have been identified in disciplines and fields as varied as physics (Park & Light 2009), geology (Cheek 2010), biology (Taylor & Meyer 2010), engineering (Flanagan, Taylor & Meyer 2010), computer science (Thomas et al. 2010), economics (Weil & Mcguigan 2010), design (Osmond & Turner 2010), history (Shopkow 2010), philosophy (Cowart 2010) and even pedagogy itself (Kinchin, Cabot & Hay 2010).

So what is the relation between paradigms and threshold concepts which follows from these similarities and connections? The above mentioned differences aside, some paradigms may be closely related to a single threshold concept. Others, which encompass a large sub-discipline of physics will contain more than just one threshold concept. On the other hand, as shall be demonstrated by examples below, some threshold concepts correspond to a paradigm while others are more adequately described as parts of a paradigm and some bear no connection to threshold concepts at all. For instance, it is hard to link Kiley & Wisker's (2010) threshold concepts relevant to general research skills such as self-directed reading to any particular physics paradigm.

What implications do these connections have for the use of philosophy in physics teaching? I propose that for those threshold concepts which are related to a paradigm or part thereof, philosophy may be seen as an aid to threshold navigation. Meyer, Land & Davies (2008) have identified four types of variation in student response to and passage through a threshold concept, which are linked to their individual backgrounds and learning styles (Kolb & Kolb 2005). Of these, subliminal variation is most strongly linked to philosophical stance, as signified by the terms epistemological, ontological and tacit:

> *'Variation in the extent of the learner's awareness and understanding of an underlying game or episteme … which may be a crucial determinant of progression (epistemological or ontological) within a conceptual domain. … Variation in such tacit understanding constitutes a mode of subliminal variation.'* (p. 408)

The identification of subliminal variation can help *'teachers … identify at which points … individual* *students might experience conceptual difficulty'* (Meyer, Land & Davies 2008, p. 408) and it *'can inform course design'* (Meyer, Land & Davies 2008, p. 408). Within the threshold concepts framework, the role of philosophy in teaching is to make tacit knowledge explicit and thus help students overcome barriers to learning posed by subliminal variation. It may be speculated that philosophy may assist the student in his entire journey across a threshold concept including the preliminal, liminal and postliminal stages.

Two examples help illustrate this point. Newtonian gravity has been identified by Meyer & Land (2003) as a threshold concept; and Kuhn (2012) has explicitly classified it as a paradigm. Its underlying metaphysical assumptions are nicely illustrated by comparing them with those of the pre-paradigm stage and the successive paradigms. Pre-Newtonian mechanics insisted that physical forces had to be mediated by physical contact between the interacting objects. Newton, on the other hand, posited gravity as a legitimate, direct means of interaction between two remote objects without any physical contact, attributing a much less tangible ontological status to the concept of a force. The succeeding paradigm of Einsteinian general relativity replaces this concept with a notion of force as mediated by curved space-time. Interestingly, current attempts to construct quantum gravity return to the contact-force concept, where gravity is due to the exchange of virtual particles. By discussing the range of philosophical assumptions underlying Newtonian gravity and its competing paradigms, teachers can help students overcome learning barriers posed by subliminal variation in the form of an instinctive discomfort with the action-at-a-distance concept.

As a second example, consider the appreciation of measurement uncertainty, which was characterised by Tymms (2013) as a threshold concept. It does not correspond to an entire paradigm, but rather to the values and possibly also exemplar components of several physics paradigms. New students typically perceive the measurement of a physical variable as unproblematic and consider error estimation as a largely superfluous nuisance. This is indicative of a realist philosophical position assuming that the true value of a measured variable exists to an arbitrary precision and is just waiting for its discovery by the scientist. Students can be sensitised to the necessity of uncertainty analysis by making their realist stance explicit and contrasting it with the competing positivist position. The latter holds that the value of a variable only exists in so far and with that precision with which the experimenter has determined it. The measurement process itself and its accompanying uncertainty thus become much more important.

4 Transformative learning: metacognition on philosophy for successful learning and research

In the previous section, I have discussed philosophy as an aid to acquiring threshold concepts. To elevate its status beyond a mere auxiliary pedagogic device, I want to develop an understanding of philosophy of science as a threshold concept in its own right. First hints towards such an understanding were given in Sect. 2 where it was suggested that philosophy might foster in students those skills which might enable them to become extraordinary scientists. To develop this idea further, I will start from the transformative character of threshold concepts and the closely related notion of transformative learning. Invoking post-modern ideas, I will then advocate philosophical metacognition and flexibility as a key to transforming students into researchers with a potential for the extraordinary.

The concept of transformative learning was first introduced by Mezirow (1978). He defines it as

> *'the process by which we transform problematic frames of reference (mindsets, habits of mind, meaning perspectives)—sets of assumption and expectation—to make them more inclusive, discriminating, open, reflective and emotionally able to change.'* (Mezirow 2009, p. 92)

This process involves *'reflecting critically on the source, nature and consequences of relevant assumptions'* (Mezirow 2009, p. 94). Can the questioning of the philosophical assumptions underlying physics paradigms be regarded as transformative learning in this sense? One needs to bear in mind that the meaning perspectives in Mezirow's (2009) framework are predominantly socio-cultural and he requires the transformation to result in *'taking action on our transformed perspective'* (p. 94), again in a societal context. If we are to regard the change of metaphysical frames of mind as transformative learning, we have to be conscious of the fact that we are employing the notion in a very limited sense and in the much more abstract context of physics learning. However, a transformation of frame of reference is certainly brought about by the questioning of philosophical assumptions during paradigm changes and this transformation has quite drastic consequences to the (scientific) society.

Kegan (2009) has refined the notion of transformational learning by distinguishing it from informational learning: *' "Informative" learning involves a kind of leading in or filling of the form ... Transformative puts the form itself at risk of change (and not just change but increased capacity)'* (p. 42). This idea immediately applies to a possible impact of philosophy: By freeing himself from the constraints of his implicit metaphysical assumptions, the physics learner can change his way of knowing and drastically broaden his capacity of knowledge.

As a measure of this increasing capacity, Kegan (2009) has suggested a hierarchy of epistemological stages. Stage models such as this have been criticised by others (Tennant 2006) and myself (Buhmann 2012). Kegan's (2009) model is vulnerable to these criticisms as he places his stages in a context of lifelong learning implying their status as prescribed developmental steps. In addition, his proposed shift of epistemological subjects becoming objects at each stage progression are not very plausible in particular for the higher stages.

Rather than adopting Kegan's (2009) entire framework, I selectively focus on his suggested final stage of the self-authoring mind as a desirable intellectual position in its own right. He links it to

> *'[p]ostmodernism [which] calls on us to win some distance even from our own internal authorities so that we are not completely captive of our own theories, so that we can recognize their incompleteness, so that we can even embrace contradictory systems simultaneously."* (p. 52)

In resonance with this idea, Tennant (2009) suggests a view where *'subjectivity is regarded as multiple, not purely rational and potentially contradictory'* (p. 151). He advertises that *'[i]t is the opening of possibilities which is the distinguishing feature of a pedagogy built on a relational view of the self'* (Tennant 2006, p. 134). Postmodernism hence advocates a self-critical reflection which allows the self to accept and embrace contradictions and turn them into an advantage.

At first glance, physics with its insistence on a unique and internally consistent description of nature seems diametrically opposed to such ideas. However, two examples may help illustrate that when applied to metaphysical beliefs, a postmodern perspective can have its place in physics. An obvious topic in physics which requires metaphysical flexibility on behalf of the student is the wave-particle duality of light. Depending on the problem or experiment that a student wishes to understand, he needs to embrace radically different ontologies of light envisaged alternatively as discrete particles or a continuous wave phenomenon. There are even cases where both of these opposing ontologies need to be embraced at the same time. What is required by the student thus transcends a metaphysical flexibility and points towards a metacognitive insight: the fact that we may be mistaken in believing that microscopic entities are understandable by analogy with distinct and familiar objects from the macroscopic world such as particles *or* waves. Quite the contrary, light is particle *and* wave at the same time.

As a second example consider quantum electrodynamics. Here, it is a matter of metaphysical debate whether forces between two atoms originate in quantum fluctuations of the atoms or those of the electromagnetic field. Either view is intrinsically associated with its own method of calculation. The two methods give equivalent results, but depending on the circumstances, either one of the may be preferable due to greater calculational ease. It may even be that only one of them is technically feasible. Only a learner who is prepared to switch between metaphysical interpretations can take advantage of the fact that there are two alternative methods of computation.

As illustrated by these examples, it is useful for both students and researchers in physics to be able and ready to switch between a variety of philosophical standpoints in order to achieve their ends. Philosophical metacognition and flexibility in this sense can be viewed as an instance of transformative learning. It requires an awareness of a range of possible philosophical positions as a starting point, but goes far beyond this mere factual knowledge. Instead, it involves reflective and divergent metacognitive thinking by making a conscious metaphysical choice which is continuously open to new challenge. Sometimes, even the decision to not adopt a well-defined metaphysical stance can be a legitimate outcome of such reflection.

Philosophical metacognition in this sense constitutes in itself a threshold concept for physics: The potential of threshold concepts to trigger epistemological transformations has already been pointed out by Timmermans (2010) in her attempts to establish a developmental framework for threshold concepts. In addition, philosophical metacognition in the envisioned form is probably irreversible (it is hard to see how students should return to the confines of a single metaphysical position after having grasped the benefits of flexible standpoints); integrative (allowing for the simultaneous acceptance of a multiplicity of theories); highly troublesome (as it is probably the only cognitive position which can enable physicists to become extraordinary scientists); but probably not bounded (being the final stage in Kegan's (2009) hierarchy).

5 Conclusion: concerning the contributions of philosophy of science to physics learning

I have argued that an attention to philosophy of science in physics teaching could have two possible beneficial effects: (i) It could help foster a deeper internalisation and understanding of central physics paradigms by the students. (ii) It might instigate a transformative learning process leading to metaphysical metacognition, enabling them to one day bring about or take part in paradigm shifts themselves. These two proposed outcomes are qualitatively very different. While the first one refers to an acceptance of the subject matter of physics itself, the second one is concerned with teaching the students how to think.

Before discussing the possible impact of my propositions, let me address some of the criticisms and objections that may be raised. Firstly, I must consider the concerns of current mainstream university teachers which may have given them reason to ban philosophy from the physics curriculum. Namely, it could be argued that philosophy could distract physics students from the main cognitive aims of this hard-pure subject (Neumann & Becher 2002): convergent, analytical rather than open-ended, critical thinking. I suggest that these concerns can be addressed by making the difference between philosophical and physical modes of reasoning explicit when introducing philosophy. In addition, the impact of history and philosophy of science on learning has been investigated in an educational study on high school teaching involving the comparison of two groups of learners (Irwin 2000). This research suggests that learners exposed to history of science did not suffer from a lack of understanding of essential concepts despite the time diverted away from their teaching.

A more fundamental criticism concerns the tension between the two envisaged functions of philosophy. While philosophy for deeper understanding serves to strengthen the commitment of students to the ruling paradigms, philosophical metacognition will have the opposite effect of loosening this commitment. As seen from Kuhn's model, this conflict is inherent in the nature of scientific progress. Any approach that seeks to make this nature explicit will also have to address the competition between the two possible modes of scientific working. I believe that in practice, it will be possible to employ philosophical reflection to serve both goals at the same time: to foster a deeper appreciation of espoused metaphysical beliefs and and awareness of alternatives. The key to success will lie in an honest conveyance of this conflict to the learners and the trust that when faced with challenges to their current beliefs in the future, they will make a well-informed decision.

Two further possible criticisms concern the scope of my analysis. Firstly, I have restricted my discussion of the impact of philosophy on deep learning to the navigation of threshold concepts. It would be certainly be interesting to explore whether philosophy can also improve the learning of physics content which does not represent a threshold concept. Secondly, my discussion was based on the assumption that university education serves to educate future researchers. However, the suggested metacognitive flexibility imposed by philosophical debate will certainly also benefit learners aiming at a career outside university.

The possible impact of history and philosophy of science on physics teaching has been studied quite intensively for school education. Comparing the results of 9 studies, Teixeira, Greca & Freire Jr (2012) have concluded that an introduction of philosophy of science to the school curriculum may enhance student learning of physics concepts; fosters an understanding of the nature of science; and probably increases the students' argumentation skills and metacognitive awareness. The review remained inconclusive about the possible effect of enhancing the appeal of science to students. The latter point is mainly of importance to physics at school, since university teaching typically deals with students who no longer need persuasion to choose physics as a subject. The other results are probably transferable to the university context, where the findings of a deeper understanding and increased metacognition may be interpreted as support for my claims.

Investigations based on school physics teaching have also indicated possible difficulties in implementing an integration of philosophy of science into the curriculum. Höttecke & Silva (2011) have identified a possible deficient teacher qualification, inadequate policies and implementation strategies and lack of appropriate textbooks as potential obstacles. These findings show that my discussion can only be the starting point in a long journey towards including philosophy of science in university physics teaching. Questions that need to be deeply reflected on concern the timing and sequencing; teaching methods and modes; possible assessment and evaluation; and whether to make the learning of philosophy compulsory or optional. In App. A, I sketch 3 tentative scenarios for including philosophy into a university physics curriculum.

These practical concerns aside, I believe that my discussion may have a profound impact on teachers, educational theorists and students. For teachers, it can trigger a deep reflection of their current practice and its basis. For educational theorists, there is a wealth of profound conceptual and practical questions which have been opened for discussion, but by no means exhaustively explored. For students, an inclusion of philosophy of science will have a strongly emancipatory effect. Ultimately, not closing our eyes and those of our students to philosophical issues will lead to a more transparent and honest approach to physics teaching the fruits of which we should no longer deny our students.

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References

Anderson, J. R. (2010), *Cognitive Psychology and its Implications*, 7th edn, New York, Worth Publishers.

Bligh, D. (1998), *What's the Use of Lectures*, 5th edn, Exeter, Intellect.

Buhmann, S. Y. (2012), From fresher to scientist: cognitivist and social constructivist perspectives on a physicist's journey through academia, Assignment, Imperial College London.

Carrier, M. (2012), Historical approaches: Kuhn, Lakatos and Feyerabend, *in* J. R. Brown (ed), *Philosophy of Science: the Key Thinkers*, London, Continuum, chapter 6, pp. 132–151.

Cheek, K. A. (2010), Why is geologic time troublesome knowledge?, *in* J. H. F. Meyer, R. Land & C. Baillie (eds), *Threshold Concepts and Transformational Learning*, Rotterdam, Sense Publishers, chapter 7, pp. 117–129.

Cowart, M. R. (2010), A preliminary framework for isolating and teaching threshold concepts in philosophy, *in* J. H. F. Meyer, R. Land & C. Baillie (eds), *Threshold Concepts and Transformational Learning*, Rotterdam, Sense Publishers, chapter 8, pp. 131–145.

Davies, P. & Mangan, J. (2010), Assessing progression in students' economic understanding: the role of threshold concepts, *in* J. H. F. Meyer, R. Land & C. Baillie (eds), *Threshold Concepts and Transformational Learning*, Rotterdam, Sense Publishers, chapter 12, pp. 193–206.

Entwistle, N. (2009), *Teaching for Understanding at University: Deep Approaches and Distinctive Ways of Thinking*, London, Macmillan.

Feyerabend, P. (1970), Consolations for the specialist, *in* I. Lakatos & A. Musgrave (eds), *Criticism and the Growth of Knowledge: Proceedings of the International Colloquium in the Philosophy of Science, London, 1965*, vol. 4, Cambridge, Cambridge University Press, pp. 197–230.

Flanagan, M. T., Taylor, P. & Meyer, J. H. F. (2010), Compounded thresholds in electrical engineering, *in* J. H. F. Meyer, R. Land & C. Baillie (eds), *Threshold Concepts and Transformational Learning*, Rotterdam, Sense Publishers, chapter 14, pp. 227–239.

Gardner, H. (2009), Multiple approaches to understanding, *in* K. Illeris (ed), *Contemporary Theories of Learning: Learning Theorists ... in Their Own Words*, London, Routledge, chapter 7, pp. 106–115.

Goswami, U. (2004), Neuroscience and education, *British Journal of Educational Psychology* **74**(1), 1–14.

Hacking, I. (2012), Introductory essay, *in* T. S. Kuhn, *The Structure of Scientific Revolutions*, 4th edn, Chicago, The University of Chicago Press, pp. vii–xxxvii.

Höttecke, D. & Silva, C. C. (2011), Why implementing history and philosophy in school science education is a challenge: an analysis of obstacles, *Science & Education* **20**(3–4), 293–316.

Howard-Jones, P. (2008), Fostering creative thinking: co-constructed insights from neuroscience and education, *Education Subject Centre (ESCalate)*, Discussions in Education Series, Bristol, Higher Education Academy, pp. 1–23.

Howard-Jones, P. A., Blakemore, S.-J., Samuel, E. A., Summers, I. R. & Claxton, G. (2005), Semantic divergence and creative story generation: an fMRI investigation, *Cognitive Brain Research* **25**(1), 240–250.

Humphris, D. (2012), College awards for excellence in teaching, Imperial College London, 11$^{\text{th}}$ December.

Illeris, K. (2009), Introduction, *in* K. Illeris (ed), *Contemporary Theories of Learning: Learning Theorists ... in Their Own Words*, London, Routledge, pp. 1–6.

Irwin, A. R. (2000), Historical case studies: teaching the nature of science in context, *Science Education* **84**(1), 5–26.

Kegan, R. (2009), What "form" transforms? a constructive-developmental approach to transformative learning, *in* K. Illeris (ed), *Contemporary Theories of Learning: Learning Theorists ... in Their Own Words*, London, Routledge, chapter 3, pp. 35–52.

Kiley, M. & Wisker, G. (2010), Learning to be a researcher: the concepts and crossings, *in* J. H. F. Meyer, R. Land & C. Baillie (eds), *Threshold Concepts and Transformational Learning*, Rotterdam, Sense Publishers, chapter 24, pp. 399–414.

Kinchin, I. M., Cabot, L. B. & Hay, D. (2010), Visualizing expertise: revealing the nature of a threshold concept in the development of an authentic pedagogy for clinical education, *in* J. H. F. Meyer, R. Land & C. Baillie (eds), *Threshold Concepts and Transformational Learning*, Rotterdam, Sense Publishers, chapter 5, pp. 81–95.

Kolb, A. J. & Kolb, D. A. (2005), Learning styles and learning spaces: enhancing experiential learning in higher education, *Academy of Management Learning & Education* **4**(2),193–212.

Kuhn, T. S. (2012), *The Structure of Scientific Revolutions*, 4th edn, Chicago, The University of Chicago Press.

Kutsar, D. & Kärner, A. (2010), Exploration of societal transitions in estonia from the threshold concepts perspective of learning and teaching, *in* J. H. F. Meyer, R. Land & C. Baillie (eds), *Threshold Concepts and Transformational Learning*, Rotterdam, Sense Publishers, chapter 23, pp. 383–397.

Land, R., Cousin, G., Meyer, J. H. & Davies, P. (2005), Threshold concepts and troublesome knowledge (3): implications for course design and evaluation, *in* C. Rust (ed), *Improving Student Learning 12: Diversity and Inclusivity: Proceedings of the 2004* 12$^{\text{th}}$ *International Symposium Improving Student Learning*, Oxford, Oxford Centre for Staff & Learning Development, chapter 4, pp. 53–64.

Land, R., Meyer, J. H. F. & Baillie, C. (2010), Editors' preface: Threshold concepts and transformational learning, *in* J. H. F. Meyer, R. Land & C. Baillie (eds), *Threshold Concepts and Transformational Learning*, Rotterdam, Sense Publishers, pp. ix–xlii.

Lave, J. & Wenger, E. (1991), *Situated Learning: Legitimate Peripheral Participation*, Cambridge, UK, Cambridge University Press.

Marshall, S. (2009), Supervising projects and dissertations, *in* H. Fry, S. Ketteridge & S. Marshall (eds), *A Handboook for Teaching and Learning in Higher Education*, 3rd edn, London, Routledge, chapter 11, pp. 132–149.

Mead, J. & Gray, S. (2010), Contexts for threshold concepts (I): a conceptual structure for localizing candidates, *in* J. H. F. Meyer, R. Land & C. Baillie (eds), *Threshold Concepts and Transformational Learning*, Rotterdam, Sense Publishers, chapter 6, pp. 97–113.

Mermin, N. D. (2004), Could Feynman have said this?, *Physics Today* **57**(5), 10–12.

Meyer, J. H. F. & Land, R. (2010), Threshold concepts and troublesome knowledge (5): dynamics of assessment, *in* J. H. F. Meyer, R. Land & C. Baillie (eds), *Threshold Concepts and Transformational Learning*, Rotterdam, Sense Publishers, chapter 4, pp. 61–79.

Meyer, J. H. F. & Land, R. (2005), Threshold concepts and troublesome knowledge (2): epistemological considerations and a conceptual framework for teaching and learning, *Higher Education* **49**(3), 373–388.

Meyer, J. H. F. & Land, R. (2003), Threshold concepts and troublesome knowledge (1): linkages to ways of thinking and practising within the disciplines, *in* C. Rust (ed), *Improving Student Learning 10: Theory and Practice—10 Years on: Proceedings of the 2002* 10$^{\text{th}}$ *International Symposium Improving Student Learning*, Oxford, Oxford Centre for Staff & Learning Development, chapter 36, pp. 412–424.

Meyer, J. H. F., Land, R. & Davies, P. (2008), Threshold concepts and troublesome knowledge (4): issues of variation and variability, *in* R. Land, J. H. F. Meyer & J. Smith (eds), *Threshold Concepts within the Disciplines*, Rotterdam, Sense Publishers, chapter 5, pp. 59–74.

Mezirow, J. (2009), An overview on transformative learning, *in* K. Illeris (ed), *Contemporary Theories of Learning: Learning Theorists ... in Their Own Words*, London, Routledge, chapter 6, pp. 90–105.

Mezirow, J. (1978), Perspective transformation, *Adult Education Quarterly* **28**(2), 100–110.

Nespor, J. (1994), *Knowledge in Motion: Space, Time and Curriculum in Undergraduate Physics and Management*, Oxon, RoutledgeFalmer.

Neumann, R. & Becher, T. (2002), Teaching and learning in their disciplinary contexts: a conceptual analysis, *Studies in Higher Education* **27**(4), 405–417.

Osmond, J. & Turner, A. (2010), The threshold concept journey in design: from identification to application, *in* J. H. F. Meyer, R. Land & C. Baillie (eds), *Threshold Concepts and Transformational Learning*, Rotterdam, Sense Publishers, chapter 21, pp. 347–363.

Park, E. J. & Light, G. (2009), Identifying atomic structure as a threshold concept: student mental models and troublesomeness, *International Journal of Science Education* **31**(2), 233–258.

Polanyi, M. (1966), *The Tacit Dimension*, Gloucester, MA, Peter Smith Publisher.

Popper, K. R. (1970), Normal science and its dangers, *in* I. Lakatos & A. Musgrave (eds), *Criticism and the Growth of Knowledge: Proceedings of the International Colloquium in the Philosophy of Science, London, 1965*, vol. 4, Cambridge, Cambridge University Press, pp. 51–58.

Ramsden, P. (1992), *Learning to Teach in Higher Education*, London, Routledge.

Rogers, J. (2007), *Adults Learning*, 5th edn, Maidenhead, Open University Press.

Scheibe, E. (2006), *Die Philosophie der Physiker*, München, C. H. Beck.

Schwartzmann, L. (2010), Transcending disciplinary boundaries: a proposed theoretical foundation for threshold concepts, *in* J. H. F. Meyer, R. Land & C. Baillie (eds), *Threshold Concepts and Transformational Learning*, Rotterdam, Sense Publishers, chapter 2, pp. 21–44.

Shopkow, L. (2010), What decoding the disciplines can offer threshold concepts, *in* J. H. F. Meyer, R. Land & C. Baillie (eds), *Threshold Concepts and Transformational Learning*, Rotterdam, Sense Publishers, chapter 19, pp. 317–331.

Sorensen, R. A. (1992), *Thought Experiments*, Oxford, Oxford University Press.

Sternberg, R. J. & Horvath, J. A. (eds) (1999), *Tacit Knowledge in Professional Practice: Researcher and Practitioner Perspectives*, Mahwah, Lawrence Erlbaum.

Taylor, C. E. & Meyer, J. H. F. (2010), The testable hypothesis as a threshold concepts for biology students, *in* J. H. F. Meyer, R. Land & C. Baillie (eds), *Threshold Concepts and Transformational Learning*, Rotterdam, Sense Publishers, chapter 11, pp. 179–192.

Teixeira, E. S., Greca, I. M. & Freire Jr, O. (2012), The history and philosophy of science in physics teaching: a research synthesis of didactic interventions, *Science & Education* **21**(6), 771–796.

Tennant, M. (2009), Lifelong learning as a technology of the self, *in* K. Illeris (ed), *Contemporary Theories of Learning: Learning Theorists ... in Their Own Words*, London, Routledge, chapter 10, pp. 147–158.

Tennant, M. (2006), *Psychology and Adult Learning*, 3rd edn, London, Routledge.

Thomas, L., Boustedt, J., Eckerdal, A., Mccartney, R., Moström, J. E., Sanders, K. & Zander, C. (2010), Threshold concepts in computer science: an ongoing empirical investigation, *in* J. H. F. Meyer, R. Land & C. Baillie (eds), *Threshold Concepts and Transformational Learning*, Rotterdam, Sense Publishers, chapter 15, pp. 241–257.

Timmermans, J. A. (2010), Changing our minds: the developmental potential of threshold concepts, *in* J. H. F. Meyer, R. Land & C. Baillie (eds), *Threshold Concepts and Transformational Learning*, Rotterdam, Sense Publishers, chapter 1, pp. 3–19.

Tymms, V. (2013), Placing physics undergraduates into a state of confusion: why we must deliberately perplex learners during their degree course, and how cognitive and socio-cultural theories of learning can assist the lecturer, Assignment, Imperial College London.

University of Cologne (2013), *Wahlfach Bachelor* [Online], Available: `http://physik.uni-koeln.de/444.html?&L=1%27%20and%20char%28124%29%20user%20char%28124%29%3D0%20and%20%27%27%3D%27` [Accessed 13th May 2013].

Von Goethe, J. W. & Williams, J. R. (1999), *Faust: A Tragedy In Two Parts & The Urfaust*, Ware, Wordsworth Editions Ltd.

Weil, S. & Mcguigan, N. (2010), Identifying threshold concepts in the bank reconciliation section of an introductory accounting course: creating an ontological shift for students, *in* J. H. F. Meyer, R. Land & C. Baillie (eds), *Threshold Concepts and Transformational Learning*, Rotterdam, Sense Publishers, chapter 20, pp. 333–345.

Weinert, F. (2004), *The Scientist as Philosopher: Philosophical Consequences of Great Scientific Discoveries*, Berlin, Springer.

Woolfolk, A. E., Hughes, M. & Walkup, V. (2012), *Psychology in Education*, 2nd edn, Harlow, Pearson.

A Towards including philosophy of science within university physics teaching

In this appendix, I intend to address the question of how the benefits of philosophy of science can be realised in practice via implementation within the physics curriculum. I will suggest several scenarios, having in mind physics teaching at Imperial College. Owing to the very standardised nature of physics teaching (Nespor 1994), my conclusions can be expected to apply to most other UK or even international universities. Physics teaching at Imperial College takes several distinct modes (Ramsden 1992), namely lectures, tutorials, laboratory work, study skills seminars (undergraduate) and one-to-one project supervision (graduate). Bearing these in mind, I see three possible levels of intensity at which philosophy can be introduced into and interwoven with the physics curriculum. They have been inspired by the level spectrum for introducing problem-based learning proposed by Rogers (2007).

Level 1: In this minimal approach, the underlying philosophical assumptions are explicitly mentioned and signposted where applicable in the course of ordinary physics lectures. This line of action can easily be implemented locally by an individual teacher such as myself, but it is unlikely to raise the student awareness necessary to achieve philosophical metacognition.

Level 2: At an intermediate level of intensity, philosophy of science can be offered as a separate lecture course or as part of a study skills course. While allowing the presentation and contrasting of a vast range of philosophical positions and ideas in a coherent form and offering a rather contained impact of philosophy, the lecture format alone is probably not very suitable for this rather discursive subject (Bligh 1998).

Level 3: For maximum impact, philosophy of science must permeate the whole physics curriculum. Philosophical debates should be included on a regular and systematic basis in tutorials, where they are linked to problem sets and preceded by short expository sessions. The rather modular nature of philosophy of science permits an ordering of the different ideas and positions according to the sequence of physics concepts and problems to which they are relevant. To utilise the benefits of their philosophy of science education, students must be actively encouraged to resort to philosophical reflection also during their postgraduate stage during project supervision (Marshall 2009).