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# Epistemological and educational issues in teaching practice-oriented scientific research: roles for philosophers of science

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## Abstract

The complex societal challenges of the twenty-first Century require scientific researchers and academically educated professionals capable of conducting scientific research in complex problem contexts. Our central claim is that educational approaches inspired by a traditional empiricist epistemology insufficiently foster the required deep conceptual understanding and higher-order thinking skills necessary for epistemic tasks in scientific research. Conversely, we argue that constructivist epistemologies (developed in the philosophy of science in practice) provide better guidance to educational approaches to promote research skills. We also argue that teachers adopting a *constructivist learning theory* do not necessarily embrace a *constructivist epistemology*. On the contrary, in educational practice, novel educational approaches that adopt constructivist learning theories (e.g., project-based learning, PjBL) often maintain traditional empiricist epistemologies. Philosophers of science can help develop educational designs focused on learning to conduct scientific research, combining constructivist learning theory with constructivist epistemology. We illustrate this by an example from a bachelor's program in Biomedical Engineering, where we introduce conceptual models and modeling as an alternative to the traditional focus on hypothesis testing in conducting scientific research. This educational approach includes the so-called B&K method for (re-)constructing scientific models to scaffold teaching and learning conceptual modeling.

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## 1 Introduction

Contemporary undergraduate and graduate programs aim to educate students to become researchers and professionals capable of conducting practice-oriented scientific research. Examples are educational programs in the engineering sciences, the medical sciences, and the agricultural and environmental sciences. It also includes educational programs in scientific disciplines such as synthetic and systems biology that aim at practical applications in the longer term. Scientific research in these domains aims at knowledge and tools that enable developing and designing interventions and predicting or investigating their consequences in the targeted real-world system.[1]

Our central question is how to teach conducting scientific research. In current academic education, scientific research is often trained in a novel educational approach called project-based learning (PjBL), where students 'learn by doing.' However, the results of this educational approach are often below expectations. Teachers find that the epistemic quality of students' research work is superficial—students do not develop a deep understanding of relevant theoretical knowledge, their approaches often lack creativity, and they do not think critically enough during the research process (personal communication).[2] We will elaborate on these expectations of teachers in Section 2 and Section 4, and analyze the issue of how to teach in conducting scientific research from an educational and an epistemological angle (in Section 2 and 3, respectively).

From the epistemological angle, we argue that teaching scientific research requires an adequate *epistemological view* in terms of which teachers and researchers talk about research practices. We suggest that an epistemology suitable for practice-oriented research practices should address three distinct aspects: how perception is related to descriptions of 'facts' and 'state of affairs' (and vice versa); how new scientific knowledge is created; and how scientific knowledge is justified (Table 1, first column). Our analysis contrasts two epistemological views (Table 1, second row), and we argue (in Section 3) that

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[1] In the engineering sciences, activities such as: experimental design, prototyping, running tests, interpreting the results, including the test results in the new model or design, and upscaling are an integral part of scientific research practices.

[2] These concerns are expressed by teachers and teaching teams involved in PjBL (project-based learning) in academic engineering education programs. We did not find any studies in the educational literature examining the extent to which PjBL supports the development of students' ability to conduct scientific research in solving the problem posed in the PjBL project.

**Table 1** Epistemological views

| Epistemology concerns three levels: | I. Traditional Logical positivist & Empiricist epistemology. | II. Constructivist epistemology |
|---|---|---|
| 1. Perception (how perception of the world turns into knowledge of facts, vice versa): | Aristotelian empiricism | Galilean empiricism |
| 2. Production (how knowledge is created): | *Context of Discovery*:<br>No logic of discovery | *Context of Construction*:<br>Methodologies and epistemic strategies in knowledge construction |
| 3. Justification (how knowledge is tested and justified): | *Context of Justification*:<br>Inductive reasoning, and the Hypothetical-deductive method | *Rational acceptability* in constructing and testing, guided by epistemic and pragmatic criteria. |

*constructivist epistemologies* suit practice-oriented research better than traditional empiricist epistemologies.

In this paper, *constructivist epistemology* refers to accounts of epistemic activities (e.g., ways of scientific reasoning) in constructing and justifying scientific knowledge. The body of literature contributing to *constructivist epistemologies* in the practice-oriented philosophy of science (Ankeny et al., 2011) is vast. Therefore, we do not aim to present a complete overview but only list several examples in this footnote.[3] Constructivist epistemologies, in short, focus on how epistemic entities (e.g., empirical laws, and scientific concepts and models) are constructed – taking into account contextual factors such as the roles of cognitive, technological, and mathematical instruments, the specific disciplinary perspective and epistemic strategies of scientific researchers, the epistemic purposes in practice-oriented research, and the roles of epistemic and pragmatic criteria as well as other normative concerns in constructing and testing.

However, while constructivist epistemologies are better suited to describe their own research practices, it appears that teachers in academia often express themselves in a vocabulary closer to the traditional empiricist view of science, even when designing educational approaches such as *project-based learning* (PjBL) that focus on learning to conduct scientific research.

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[3] Examples of contributions to constructivist epistemologies: the critical evaluation of *laws of nature*, initiated by Cartwright (1983, 1989, 1999); the emphasis on the role of *interventions* in scientific research by Hacking (1983); the issue of *applying science* (Boon, 2006; Cartwright, 1974); the roles in scientific reasoning of *analogies* (Hesse, 1966; Nersessian, 2009b), *concepts* and *formation of concepts* (Rheinberger, 1997, Feest, 2008, Andersen, 2012, Nersessian, 2009b, Boon, 2012, Rouse, 2011, 2015), *conceptual change* (Andersen, 2012; Andersen & Nersessian, 2000; Kuhn, 1970; Nersessian, 1992), *scientific understanding* (De Regt et al., 2009), *models* (Bailer-Jones, 2009; Morrison & Morgan, 1999), *modeling* and *model-based reasoning* (Boon & Knuuttila, 2009; Giere, 1988, 1999, 2010; Giere, 2006; Knuuttila & Boon, 2011; Magnani, 2014; Magnani & Bertolotti, 2017; Nersessian, 2009a; Nersessian & Patton, 2009), *epistemic and pragmatic criteria* (Chang, 2009, 2014, 2017, 2020; Hacking, 1992; Kuhn, 1970), and *inductive risk and values* (Biddle, 2016; Douglas, 2000; Kukla, 2016; Wilholt, 2009, 2013); the role of context in deriving *phenomena* from *data* (Bogen & Woodward, 1988; Leonelli, 2011, 2014, 2019; Leonelli & Boumans, 2020); the roles of *perspectives* through theories, concepts, and technological instruments (Boon, 2020a; Giere, 2006; Van Fraassen, 2008); the challenges of *interdisciplinarity* (MacLeod, 2018,); and, the role of *experimentation* and *technological instruments* (Hansson, 2015; Radder, 2003; Rheinberger, 1997).

Therefore, our educational angle concerns educational approaches in teaching scientific research (Section 2). Project-based learning (PjBL) is motivated by a so-called *constructivist learning theory*. *Learning theories* address *how students learn*. Constructivist learning theories are a response to so-called *cognitivist learning theories*.[4] In short, constructivist learning theories emphasize the importance of experiences and posit that students *learn by doing*, for example, by engaging with concrete contexts and authentic practices. However, constructivist learning theories have many faces much discussed in scholarly literature. For our purpose, we focus on how constructivist ideas have inspired educational approaches such as PjBL.

Relevant here is that constructivist learning theories generally emphasize that 'learning by doing' should be supported by appropriate *scaffolding*. Vygotsky (1978, Orig. 1920th) introduced the general concept of 'scaffolding' as a crucial aspect of constructivist learning theories. Scaffolding was initially described as the support provided by the more knowledgeable adults or peers to the learners to complete tasks beyond their level of competence (Wood et al., 1976). Nowadays, it is also defined as adaptive and temporary support to develop learners' skills and enhance knowledge (Lin et al., 2011). Moreover, educators and educational research have expanded the focus on scaffolding from teachers and peers to tools, reflection guides, and frameworks designed to help learners develop skills and knowledge beyond their reach (Smit et al., 2013). Our reference to scaffolding includes the latter interpretation. However, in educational practice, there is often a lack of scaffolding in PjBL that focuses on learning how to conduct scientific research.[5,6] We argue that this neglect of the crucial role of scaffolding may be due to a traditional epistemology at the root of how educators think and speak about scientific research. Traditional epistemologies tend to neglect the crucial role of concepts and structures required to 'see' something when 'learning by doing' and 'letting students find out themselves' (also see Table 1 and footnote 4).[7] We explain this misconception by the distinction (proposed by Matthews, 1993)

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[4] *Cognitivist* learning theory focuses on the acquisition of knowledge and internal mental structures. It emphasizes the crucial role of concepts and structures in students' learning processes to receive, organize, understand, and store information. Knowledge acquisition is described as a mental activity that involves internal coding and structuring by the learner. The learner is seen as a very active participant in the learning process. Teachers help students make sense of, organize, and link knowledge. In addition, teachers provide learning strategies that promote students' learning. However, a potential shortcoming of cognitivist approaches is the connection between knowledge, concepts, and theories, on the one hand, and concrete experiences related to these epistemic entities, on the other (Ertmer & Newby, 2013, repr. 1993).

[5] This finding in actual educational practice, in which we engage as philosphers and educational researchers, is supported by a recent systematic review of literature on teaching interdisciplinarity in engineering education. PjBL is a widely used educational approach to promote students' skills in interdisciplinarity and interdisciplinary research, but we found virtually no evidence that the development of these skills is actively supported (i.e., scaffolded) in PjBL projects (Van den Beemt et al., 2020). The general premise in concrete educational settings seems to be that these skills develop naturally in PjBL.

[6] Relevant to our context is that, while the concept of scaffolding has been studied significantly in early learning and school education, the literature on the use of scaffolding in higher education is scarce.

[7] A closely related concern discussed in educational psychology is that the constructivist approach in educational practices (as in PjBL) may come at the expense of providing students with adequate concepts, structures, and learning strategies emphasized in cognitivist learning theories (footnote 4). Ertmer and Newby (2013, repr. 1993), therefore, defend combining insights from cognitivist and constructivist approaches on learning-theoretical grounds. We will add that this is also necessary based on the constructivist epistemology appropriate to actual research practices. This epistemology necessitates the provision of scientific concepts, structures, and learning strategies to teaching scientific research.

between Aristotelian versus Galilean empiricism at the level of perception (Table 1 and Section 3).

Altogether, it is essential to recognize that adopting a *constructivist learning theory* does not necessarily imply that teachers embrace a *constructivist epistemology* – on the contrary, in educational practice, constructivist learning theories are often combined with traditional empiricist epistemologies. The role of traditional epistemological views may explain why educational approaches such as PjBL motivated by constructivist learning theories often ignore the importance of scaffolding. Conversely, constructivist epistemologies explain the crucial role of scaffolding in constructivist educational approaches.

These insights into the epistemological and educational issues in teaching practice-oriented scientific research have helped us better understand teachers' difficulties when implementing PjBL projects. Section 4 illustrates how philosophers of science helped implement a constructivist epistemology in an educational redesign of PjBL in a bachelor's program in biomedical engineering. In this PjBL project, students conduct scientific research to develop a biomaterial that remedies a medical condition. Crucial to our approach was to steer away from a vocabulary in which students first learn to think about scientific research in terms of research questions and testing hypotheses. In our alternative approach, students learn that scientific research involves *constructing* scientific knowledge and understanding for a specific epistemic purpose (e.g., to develop a biomaterial that meets specified functions and requirements). That is why we introduced *conceptual modeling* as an overarching skill in scientific research. The resulting scientific knowledge and understanding of the problem, and then a possible solution, is called conceptual models. Students are scaffolded by *learning assistants* trained in conceptual modeling, who assist them in developing their scientific understanding of the problem and possible solutions by learning to ask questions, search answers in the literature, and select and implement relevant information into their 'story' (i.e., the conceptual model). The so-called B&K method for (re)-constructing scientific models (Boon, 2020b) is thus used as a scaffold in teaching and learning conceptual modeling. In this way, students learn to recognize the construction of scientific models as a crucial activity in scientific research and experience that the resulting model is used iteratively as a 'tool for thinking' in further research.

## 2 Teaching practice-oriented scientific research

### 2.1 Twenty-first-century professionals: The ability to conduct scientific research

Regulatory bodies of many countries such as *The* Bologna Working Group (2005), *The National Accreditation Organisation* (NVAO, 2005) in the Netherlands and Flanders, and *The Accreditation Board for Engineering and Technology* (ABET, 2018) in the USA, urge that the complex societal challenges of the twenty-first-Century call for professionals having a unique set of professional and academic skills.

Our focus is the ability to conduct scientific research to generate knowledge and tools for dealing with these complex societal challenges (i.e., knowledge and tools not only to *understand* but also to *improve* the world). The knowledge, skills, and attitude required for such comprehensive ability are often referred to as intended learning outcomes (ILOs) in education policy documents. The ILOs related to research in ABET (2018) assume that graduates have an ability such as to: “identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics,” “develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions,” and “acquire and apply new knowledge as needed, using appropriate learning strategies.” Meijers et al. (2005) put more weight on *the ability to conduct scientific research* than ABET (2018). They emphasize the task of “gaining *new* knowledge and *new* insights in a goal-oriented methodological way,” which they consider fundamental to any academic program, including university-level engineering programs.

### 2.2 Project-based learning (PjBL) as an approach to teaching and learning scientific research

The educational challenge is how to teach all this. The call for professionals with a much broader professional and academic skill-set (than what academic education initially aspired) and new insights into how people learn have led to new educational approaches. Higher education is increasingly changing from a traditional *instructivist* “chalk and talk” lecture-practice approach to *constructivist* approaches such as project-based learning (PjBL), problem-based, and challenged based learning (Du et al., 2013; Fernandes, 2014; Gavin, 2011; Lehmann et al., 2008; Mills & Treagust, 2003; Moallem, 2019; Vila et al., 2017).

We will focus on PjBL and how this educational approach teaches to conduct scientific research. The main features of PjBL are the application-oriented approach and creating a conducive learning environment that provides the challenges that professionals and experts usually face in real-life (Kanigolla et al., 2014; Kolmos & Graaff, 2015; Roessingh & Chambers, 2011). These challenges require professionals to have a deep conceptual understanding of the topics and the ability to critically evaluate and use the knowledge in authentic contexts (Bédard et al., 2012, Woods, 2012, Kokotsaki et al., 2016, Beier et al., 2019).[8]

Policy documents highlight the significance and the potential to reach the intended learning outcomes (ILOs) promoted through these educational strategies, particularly regarding the broader *professional* skills such as problem-solving, communication, and collaboration (Alorda et al., 2011; Chen & Yang, 2019; Guo et al., 2020; Teixeira et al., 2020; Vila et al., 2017). However, it has not been significantly demonstrated that, through PjBL approaches, students also develop a deep conceptual understanding of scientific knowledge relevant to their discipline and higher-order thinking skills (HOTS) such as epistemic, critical, and creative thinking (Masek & Yamin, 2011; Mills & Treagust, 2003; Pinho-Lopes & Macedo, 2014; Polanco et al., 2004; Van den Beemt et al., 2020). Such understanding and skills are crucial to conducting scientific research aimed at new knowledge relevant to the practical problem.

This finding in the educational research agrees with experiences from teachers involved in PjBL education at our university. In teacher-team meetings, they repeatedly

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[8] We recommend Sawyer (2014) for an accessible overview of learning theories. Sawyer shows that new ideas about learning are based on a number of different sources: cognitive psychology, studies of how scientists actually work, and an epistemology away from logical empiricism.

report that students deliver superficial projects due to not sufficiently managing to integrate disciplinary knowledge into their projects and not readily grasping how to link research and design in a problem-solving task. More specifically, teachers believe that students lack *understanding* of scientific theories —which introductory courses intend to teach—, so that students often do not use scientific theories and scientific ways of reasoning (i.e., 'scientific thinking') in formulating and dealing with research questions. Moreover, teachers often claim that students lack a *critical* and *investigative* attitude towards scientific research (Ahern et al., 2019).

These findings suggest that the current PjBL approaches do not substantially contribute to the achievement of ILOs required for scientific research in complex problem-solving. Also, a more substantial understanding of how students can be supported to understand scientific research is lacking.

### 2.3 How to teach higher-order thinking skills (HOTS) needed in conducting scientific research

Our concern is the intended learning outcomes (ILOs) related to the knowledge, skills, and attitudes required to conduct scientific research. Realizing these ILOs requires developing deep conceptual understanding in concord with *higher-order thinking skills* (HOTS). The term 'thinking skills' refers to cognitive processes or intellectual capacities (Small, 2020), while the qualifier 'higher-order' alludes to abilities such as: integrating, reasoning using abstract concepts, and manipulating abstract concepts (Fischer, 1980, King & VanHecke, 2006). The more specific ability to conduct scientific research, in particular research related to complex real-world problems, involves HOTS that concern students' ability to: *systematically analyze 'real' problems* (Meijers et al., 2005), *apply science* (Boon, 2006), *integrate heterogeneous information* (Boon, 2020b; Mansilla, 2010; Van Baalen & Boon, 2015, 2017), *reason and reflect* (Meijers et al., 2005), and *to think critically* (Ahern et al., 2019; Miri et al., 2007; Payan-Carreira et al., 2019), *analytically* and *analogically* (Nersessian & Newstetter, 2014), *creatively* (De Vries & Lubart, 2019) and *interdisciplinary* (ABET, 2018; Mansilla, 2010; Meijers et al., 2005; Nersessian & Patton, 2009; Spelt et al., 2009; Van den Beemt et al., 2020).

The educational challenge is how to teach and learn these HOTS. In current higher-education practices, the idea is widely adopted that HOTS develop 'naturally' in educational approaches that promote 'learning by doing' such as PjBL (Kolmos & Graaff, 2015; Mills & Treagust, 2003; Strobel & Van Barneveld, 2009). However, educational research provides ample evidence that the development of HOTS requires deliberate training and scaffolding, rather than developing 'naturally' in PjBL settings (Barzilai & Zohar, 2014; Brookhart, 2010; Collins, 2014; Hattie, 2010; Higgins et al., 2005; Hmelo-Silver et al., 2007; Khosa & Volet, 2013; Kirschner et al., 2006; Reiser & Tabak, 2014; Soufi & See, 2019; Zohar & Barzilai, 2013).

We analyze this shortcoming of current educational practices that aim to train students in conducting scientific research from an educational angle (next section) and an epistemological angle (in Section 3).

## 2.4 Constructivist learning theories

Problem- and Project-based Learning (PBL and PjBL) are motivated by learning theories referred to as *constructivism*. We will suggest that the limited success in promoting deep conceptual understanding and HOTS has more to do with the lack of systematic and purposefully designed 'scaffolds' to support students in developing this than with flaws inherent to constructivist learning theories.

To better understand the issues raised so far, we need to delve a little deeper into constructivist learning theories (*constructivism* for short). Learning theories such as constructivism seek to explain the cognitive processes of learning. Roughly, constructivism proposes that people learn by structuring knowledge that is new to them ('assimilation') and connecting this to their prior knowledge and experience, which usually requires a partial reconstruction ('accommodation') of the existing cognitive structures (Fosnot & Perry, 1996; Piaget, 1970). In this way, knowledge gets *meaning* for the learner, and the learner begins to *understand* the knowledge, for example, the knowledge offered in a science course. In brief, constructivism assumes that the processes of *meaning formation* and *developing understanding* (e.g., of a scientific concept) involve that learners establish relationships and connections between prior knowledge and experiences (e.g., Bélanger, 2011, also see footnote 4).

Two remarks are important for a proper understanding of constructivism. First, constructivist learning theories do not claim that students are supposed to *construct* scientific knowledge (e.g., Newton's theory). The point is instead that the students develop 'deep conceptual understanding' (of the *meaning*) of a scientific concept or theory by establishing relationships with their own experiences (generated in interactions with the environment, including objects, teachers, and experts) and with knowledge (e.g., concepts and structures) that they already understand. A didactic approach to achieve the mentioned understanding is given in the history and philosophy of science (HPS) tradition. Authors in this tradition (e.g., Chang, 2004; Conant, 1957; Matthews, 2002, 2014) suggest letting students *'reconstruct' a scientific concept or theory* by conducting experiments and reasoning processes, thus letting them experience its genesis along the lines of its history in science. Another didactic approach promoted in this context is *conceptual mapping*. In this approach, students deepen their understanding of a concept by drawing relationships with other concepts, through which a concept gets contextualized (e.g., Edmondson & Novak, 1993, Novak, 2010). Other authors argue that learning processes to understand scientific concepts and theories involve 'knowledge restructuring' in the sense of *conceptual change* (Duschl & Gitomer, 1991).[9] Still another didactic approach is *model-based reasoning* (e.g., Nersessian, 1992, 2009a, Magnani ed. 2014, Magnani & Bertolotti eds. 2017), which involves encouraging students to construct models of a problem or a system (e.g., Newstetter, 2005, Schwarz, et al., 2009, Duschl & Grandy, 2013, Boon, 2020b). Scientific concepts and models are the typical epistemic entities produced in practice-oriented scientific research. This is why we have implemented these authentic activities (i.e., the construction of scientific concepts and models) in PjBL practices aimed at teaching and learning scientific research (Section 4).

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[9] Originally, educational approaches such 'conceptual mapping' and 'knowledge restructuring in the sense of conceptual change' were based on cognitivist learning theories. Also see footnote 4.

Our second remark concerns the crucial role of interactions with competent others and culture, referred to as 'the mediation of more knowledgeable others' and 'cultural mediation.' This theory is often called *social or socio-cultural constructivism*.[10] Constructivist learning theories generally consider the development of cognition as a *mental* process of individual learners. Socio-cultural constructivism emphasizes the role of interaction with the social-cultural world for learning. On the one hand, such interaction provides clear-cut *information* (e.g., written sources such as textbooks and scientific articles) and tools (e.g., *scaffolds*, *methods*, and *conceptual frameworks*), and on the other hand, allows for collaboration and conversation with competent others (e.g., teachers and experts) who guide the student in *seeing* or *recognizing* connections and meaningful relationships, and also in *articulating* what would otherwise remain 'mental' (Sawyer, 2014).[11]

Project-based learning (PjBL) is an educational approach inspired by constructivist learning theories. A burning question —based on our own experiences in this type of education and on findings in the literature as summarized above— is why the role of scaffolds is so often (deliberately) ignored in the educational design and why it is often assumed that students' project work should be supervised by 'non-expert' tutors in the role of process facilitator.

Teachers who strongly believe in the correctness of minimal guidance in PjBL use phrases such as: 'learn-by-doing,' 'self-directed learning,' 'let them discover it themselves,' 'they learn by making errors,' 'do not give them answers,' 'they must find their own way,' 'give them a pile of books and let them find the knowledge themselves,' 'they can consult an expert for questions,' 'providing methods will indoctrinate them,' and 'tutors should be facilitators of the process, not experts (as experts are tempted to give answers and guidance).' This approach of minimal guidance disregards important insights from cognitivist learning theories about acquiring and understanding knowledge (see footnote 4). We conclude that educational literature provides sufficient grounds to accept the crucial role of scaffolding in PjBL.

In addition, we conjecture that the omission of scaffolding and the downplaying of expert roles of tutors in PjBL approaches is due to a traditional empiricist epistemology directing how teachers think and speak about conducting scientific research (see Table 1). In a naïve understanding, the traditional epistemology supports the belief that observations 'speak for themselves,' implying that students do not need guidance to interpret and contextualize what they see, experience, or read (see Section "Aristotelian versus Galilean empiricism" below).

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[10] In educational sciences, two constructivist learning theories are usually distinguished, namely *radical constructivism* (as an interpretation of Piaget, 1970) and *socio-cultural constructivism* (as an interpretation of Vygotsky, 1978, 2012). Useful summaries are given by Confrey (1994, 1995), Fosnot and Perry (1996), Liu and Matthews (2005), Bélanger (2011), and Sawyer (2014). Our focus is on the latter.

[11] To illustrate what is meant by 'seeing,' 'recognizing,' and 'articulating,' promoted in a socio-constructivist learning theory (c.f. Vygotsky, 1978), it is worth considering this quote from Joe Rouse: "Conceptual articulation enables us to entertain and express previously unthinkable thoughts, and to understand and talk about previously unarticulated aspects of the world" (cited from a conference paper at SFSU, Rouse, March 2009; also see Rouse, 2011, 2015).

## 3 Constructivist epistemology

### 3.1 The need for a vocabulary to talk about the construction of knowledge in research practices

Although constructivist epistemologies are widely accepted —especially in recognizing that scientific theories can change and do not provide absolute truth—, it appears challenging to translate these insights into a vocabulary that productively grasps scientific research practices. We often observe that students, teachers, and researchers talking about science tend to combine a relativist-subjectivist vocabulary that stresses the social-constructivist character of science (which expresses an outsider/observer perspective on science), on the one hand, and a realist-objectivist vocabulary (usually combined with a traditional empiricist epistemology) when they talk about their scientific discipline or research (which expresses an insiders perspective of science), on the other.[12]

The conflicting philosophical vocabularies (often present in one person) illustrate that students, teachers, and researchers do not yet have an adequate vocabulary to talk *about* the *construction* of knowledge in scientific research practices. In promoting a constructivist epistemology, we follow in the footsteps of Hanson (1958), who argues against the strict distinction between the context of discovery and justification maintained by philosophers in the logical empiricist and H-D tradition. Hanson pledges that:

"more philosophers must venture into these unexplored regions in which the logical issues are often hidden by the specialist work of historians, psychologists, and scientists themselves. We must attend as much to how scientific hypotheses are caught [discovery], as to how they are cooked [justified]" (Hanson, 1958, 1089).

We take Hanson's suggestion to heart and propose that educational practices aimed at teaching and learning scientific research require an epistemology that adequately accounts for the justification of knowledge *and* the construction process.

### 3.2 Constructivist epistemology for the construction of new knowledge

Table 1 compares a traditional empiricist (including the hypothetical-deductive method) and a constructivist epistemology by distinguishing between perception, production, and justification of knowledge. Here, we further develop this distinction to foster a vocabulary better suited to practice-oriented scientific research. Importantly, constructivist epistemologies emphasize the role of context, whereas traditional epistemologies emphasize the universal character of knowledge. Accordingly, typical epistemic entities in traditional epistemologies are (universal) theories and laws, whereas constructivist epistemologies usually focus on (context-dependent) scientific concepts and models, and empirical laws.

Furthermore, in traditional empiricist epistemologies, the prevalent idea about the nature of knowledge (related to what is considered the *aim of scientific research*) focuses on the (context-independent) *descriptive* nature of knowledge. In contrast,

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[12] This combination of apparent contradictory presuppositions about science can even be observed in the list that summarizes the established view on the *nature of science* (NOS) that must be taught in secondary science education (McComas et al., 1998, p. 513; McComas, 2014).

constructivist epistemologies pay attention to its (context-dependent) functional character, sometimes referred to as knowledge being an *epistemic tool* used in further reasoning about, for example, a practical problem.

These differing views about the character and purpose of knowledge also entail differing ideas about what *scientific methodology* should achieve. For example, traditional empiricist epistemologies focus on collecting evidence for confirmation or falsification of theories and laws based on the outcomes of tests, such as statistical analysis of empirical data (primarily inductive reasoning) or experimental tests of hypotheses (primarily hypothetical-deductive reasoning). On the other hand, constructivist epistemologies focus on *rational acceptability* in the knowledge construction process — i.e., epistemic and pragmatic criteria for accepting knowledge guide these methodologies. Traditional empiricist and constructivist epistemologies share epistemic criteria —such as 'empirical adequacy,' 'internal logical consistency,' 'coherency with accepted knowledge,' and 'statistical significance'— but adhere to different pragmatic criteria. Examples of pragmatic criteria in traditional epistemologies are 'universality,' 'generality,' 'simplicity,' and 'explanatory strength.' On the other hand, constructivist epistemologies emphasize *epistemic uses* of knowledge in application contexts, which involves pragmatic criteria that guide choices in constructing and testing new knowledge. Examples are 'relevance to epistemic purposes,' 'internal coherency and intelligibility (to allow for reasoning based on the model),' and 'explanatory and predictive power' — often next to normative criteria related to a broader context.

Finally, constructivist epistemologies also address the contribution of *instruments* that shape knowledge, such as experimental set-ups and measurement techniques, mathematical tools, and scientific concepts and conceptual frameworks, which are continuously developed and justified in research practices.

### 3.3 Aristotelian versus Galilean epistemology in constructivist learning theories

We use Matthews' (1993) analysis of apparent epistemological assumptions in constructivist learning theories to elaborate how (usually implicitly held) philosophical presuppositions can play a role in how constructivist learning theories are translated into teachers' educational approach and educational vocabulary.

Based on Matthews, we distinguish between what he calls *Aristotelian empiricism* and what we will call *Galilean empiricism* (also see Table 1). Matthews summarizes Aristotelian empiricism as:

> "an empiricist, individualistic, reflective [mirroring] or correspondence theory of knowledge (the 'spectator theory'): knowledge was something generated by, and residing inside, an observer" (Matthews, 1993, 363).

Galilean empiricism, on the other hand, makes a distinction between:

> "the *theoretical object of science*, which is a system of mathematically expressed definitions, principles, concepts, and relations, and the *real objects of science*, which are the materials, events, and objects in the world that are grasped,

> described, and by suitable instrumentation and experimentation, manipulated by scientists," (ibid 365, our emphases).

Crucial to Galilean empiricism is that scientific knowledge is not derived from carefully looking at, say, a real pendulum. Instead, scientific researchers approach what they *see* (e.g., the real pendulum) with a collection of conceptual and mathematical instruments (partly invented by the same researchers) to *construct* a *representation* or a '*description.'* The constructed representation or description is the *theoretical* object. To emphasize his point, Matthews quotes Pierre Duhem:

> "[if the scientific researcher enters the laboratory] without theory it is impossible to regulate a single instrument or to interpret a single reading; we have seen that *in the mind of the physicist there are constantly two sorts of apparatus*; one is the *concrete apparatus* in glass and metal manipulated by him, the other is the schematic and *abstract apparatus* which theory substitutes for the concrete and on which the physicist does his reasoning [Duhem, 1906/1954, p. 182]" (cited in Matthews, 1993, 366, our emphases).

Galilean empiricism emphasizes that scientific researchers use all kinds of conceptual, technological, and mathematical instruments —or apparatus, as Duhem puts it— to arrive at a 'description' of what they 'see' when looking at the real world. This account of scientific research explains how a theoretical object (or phenomenon) is *constructed* and subsequently referred to by a scientific concept (e.g., the ideal harmonic oscillator). Constructivist epistemology agrees in this regard with Galilean empiricism.

Assume that, as Matthews suggests, teachers (implicitly) combine a constructivist learning theory with Aristotelian empiricism, denying the inherent role of concepts and theories in 'describing' what someone 'sees' in the laboratory. Moreover, assume that these teachers also adopt a (Piagetian) constructivist learning theory stressing that learning processes should happen 'naturally.'[13] Perhaps, these are the philosophical and educational presuppositions based on which teachers think scaffolding in teaching and learning to conduct scientific research (e.g., in PjBL) is unnecessary. In short, a constructivist learning theory does not necessarily imply that teachers embrace a constructivist epistemology – on the contrary, constructivist learning theories can be combined with traditional empiricist epistemologies. On the other hand, constructivist epistemologies make the crucial role of scaffolding in constructivist educational approaches such as PjBL much more plausible.

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[13] In later work, Piaget nuances the idea of natural development. He explains that his "earlier model had proved insufficient... The central new idea is that knowledge proceeds neither solely from the experience of objects nor from an innate programming performed in the subject but from successive constructions," (Fosnot & Perry, 1996, p.18).

### 3.4 A vocabulary based on constructivist epistemology guiding the educational design of PjBL

In our contribution to redesigning PjBL in a biomedical engineering bachelor program, a constructivist epistemology guides our vocabulary for discussing scientific research. Thus, instead of explaining scientific research firstly in terms of hypotheses and tests, we propose that modeling and model-based reasoning are central to the construction of knowledge in practice-oriented scientific research practices (Bailer-Jones, 2009; Boon, 2020b; Boon & Knuuttila, 2009; Magnani, 2014; Magnani & Bertolotti, 2017; Morrison & Morgan, 1999; Nersessian, 2009a; Newstetter, 2005). In particular, we focus on conceptual modeling[14] (rather than mathematical modeling, which is much more common as a learning objective).[15] Furthermore, we emphasize that scientific knowledge construction involves various instruments (technological, conceptual, mathematical) and reasoning methods (e.g., deductive, inductive, abductive, analytical, analogical, interpretative, integrative, creative, imaginative, and mathematical). At the same time, we seek to avoid extreme forms of relativism and subjectivism by emphasizing the crucial roles of (1) the material world, which puts restrictions on what researchers can claim, (2) epistemic and pragmatic criteria that impose limitations and demands on the many modes of scientific reasoning, and more broadly (3) the socio-cultural world, understood as consisting of scientific communities that develop, establish (justify) and convey both the knowledge of its field as well as how to handle epistemic and pragmatic criteria in scientific reasoning towards new knowledge (e.g., Oreskes, 2019).

A constructivist epistemology that fits our goal focuses on “how knowledge is constructed in practice-oriented scientific practices.” This question adds several other elements. For example, it emphasizes that knowledge construction is usually directed towards a specific *epistemic purpose*. Moreover, it assumes that the *justification* of the knowledge (e.g., the conceptual model) largely occurs in the *construction* process (Boumans, 1999; Knuuttila & Boon, 2011). Accordingly, students are requested to justify why existing scientific knowledge implemented in the model ‘applies’ (e.g., is relevant to describe or explain the medical condition); and which kinds of measurements they would need to investigate the phenomenon; and also why, when judged from the epistemic purpose, certain simplifications are appropriate (Boon, 2020b). Thus, the constructivist epistemology addresses the construction process’ ‘logic’ or ‘method’ (c.f. Hanson, 1958). This ‘logic’ is turned into a scaffold that guides students in the construction of conceptual models. The scaffold, called “a method for (re-)constructing scientific models” or B&K method for short (Boon, 2020b), is not an algorithm but teaches students to systematically recognize and understand the aspects that need to be ‘built into’ the model (Boumans, 1999) along with critical reasoning considering aspects just mentioned.

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[14] See for example Knuuttila and Boon’s (2011) analysis of how Sadi Carnot constructed the model of the ideal heat engine. Carnot’s model can be considered an example of a *conceptual* model.

[15] Our focus on (conceptual) modeling does not mean that we deny the roles of inductive, deductive, or hypothetical-deductive reasoning (including the formulation of hypotheses) in scientific research. Instead, these kinds of reasoning are considered part of the modeling activities.

# 4 Philosophy of science in educational practice

## 4.1 Implementing conceptual modeling for learning to conduct scientific research

In 2013, our university's bachelor program Biomedical Engineering adopted a project-based learning (PjBL) pedagogy. The bachelor program consists of 12 modules, each designed around a theme in which students carry out a project assignment in project groups and receive courses related to the project theme. For example, the first module is organized around the theme 'biomaterials.' The project assignment is to design a biomaterial for a biomedical problem such as 'replacing the oesophagus after cancer.' In addition, the module includes courses linked to the theme, such as organic, inorganic, and polymer chemistry, biochemistry, anatomy, physiology, mathematics, and statistics.

In 2018, the educational program was evaluated, which resulted in several challenges, mainly those already mentioned in the previous section (e.g., the limited uses of scientific knowledge in their projects, leading to results below expectations).

The first author of our article was, as a philosopher, involved in the teacher-team to advise on the program's redesign. Her advice consisted of implementing an alternative epistemological view and pedagogical approach to project-based learning (PjBL). In the original approach, the student-project assignment suggested an empiricist methodology (specifically, the hypothetical-deductive method, consisting of observation, research-question, hypothesis, and test, Hempel, 1966). The point is that the assignment's description agrees with the *vocabulary* that teachers and researchers commonly use when talking *about* research. However, it does not agree very well with how researchers go about when conducting a research project. The teachers agreed that *scientific modeling* is central to their scientific research and design practices and that hypothesis testing is only one aspect.[16]

We introduced the notion of *conceptual* modeling as distinct from *mathematical* modeling. Thus, the 'ability to construct conceptual models' became the central learning objective. In developing the students' research-project assignment, we used (parts of) the method for constructing scientific models proposed in Boon (2020b) as a scaffold for guiding the students. The assignment consists of two consecutive phases.

The assignment in phase 1 is to develop a conceptual model of the *problem*, for example, a scientifically informed conceptual model of the oesophagus and its functioning in the body. The students have to develop the model in such a way that it allows for thinking about possible biomaterial solutions to replace the oesophagus. Furthermore, the model must allow for pointing out the *functional criteria* the solution should meet. While constructing the model, the students become aware that the context and purpose need to be considered – for example, to see the difference between the conceptual model of the oesophagus constructed for their epistemic purpose (i.e., to design a replacement utilizing a biomaterial) and the conceptual model that a surgeon or oncologist has in mind when thinking

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[16] In developing this approach we are indebted to the pioneering work of Nersessian and Newstetter c.s. at Georgia Tech (e.g., Nersessian & Newstetter, 2014; Newstetter, 2005).

about surgery. In the modeling process, the students investigate the problem and the relevant scientific literature. We assume that this approach contributes to developing their higher-order thinking skills (HOTS, e.g., analytical, integrative, and critical thinking). The assignment in phase 2 is to construct a conceptual model for their design-idea to *solve* the medical problem, which next to the HOTS just mentioned, also requires creative thinking.

The introduced 'conceptual modeling approach' aims to solve the mentioned educational problems. Its implementation in the module fits a constructivist epistemology. First, it assumes a clear link between scientific research and design (reflected in the assignment's two phases). Second, it allows for the use of scientific knowledge in ways that go beyond deduction and induction in traditional empiricist epistemology. Furthermore, in this approach, students begin to model a problem or design-idea based on their rudimentary understanding of the problem or solution. Thus, the preliminary conceptual model becomes an *epistemic tool* for further development of the model (Knuuttila & Boon, 2011). Finally, it functions as a hub where heterogeneous information (scientific and empirical knowledge, relevant variables and parameters, measurement methods, pragmatic criteria concerning the solution) is collected and integrated into a coherent whole (Nersessian & Patton 2009, Boon, 2020b).

How the 'conceptual modeling approach' is implemented in this module also agrees with socio-constructivist learning theories. In learning to construct conceptual models, the project groups are scaffolded (i.e., learning to use a method for constructing a scientific model, Boon, 2020b) by learning-assistants whom we educated for this role. They play a much more significant role in the students' learning pathway than 'tutors as non-expert facilitators' in more common approaches to PjBL (e.g., Van den Beemt et al., 2020). Crucial to their role is to make students aware of the need to ask relevant questions to develop the conceptual model. For example, "how does this work," "what is the composition of tissue," "how does it get its elasticity and permeability," and "what are (advantages/disadvantages) of existing solutions"? Students will have to search textbooks and scientific literature for information on these questions that they must integrate into the conceptual model. This process will lead to new questions, new searches, and answers that will deepen the understanding in an iterative process.

Students' HOTS are promoted because they are encouraged to analyze, contextualize, articulate, search and apply relevant scientific knowledge, integrate heterogeneous kinds of information, and evaluate the emerging conceptual model against epistemic and pragmatic criteria such as adequacy, consistency, coherency, relevance, intelligibility, and usefulness in regard of the scientific and practical problem-context at hand.

### 4.2 Interdisciplinary research by philosophers of science and educational scientists

Evaluating whether this constructivist epistemology and pedagogical approach to PjBL successfully promotes students' HOTS for conducting scientific research on complex problems requires solid educational research. At present, our team —consisting of philosophers of science, educational researchers, curriculum developers, teachers, the learning-assistants, and students— is conducting an interdisciplinary research project aimed at (i) (empirically) investigating the effects of the redesign on students' learning outcomes (ILOs), (ii) developing a more explicit conceptualization of the ILOs concerning the HOTS required in scientific thinking when conducting scientific research, and (iii) improving the educational design of PjBL approaches to reach these ILOs more successfully, including the development of effective scaffolding and the teaching of philosophy of science.[17]

We can already share some salient observations. Initially, the first-year students got confused about the notion 'conceptual modeling,' but in their reflections at the end of the project, they reported that "when the penny dropped," they found it straightforward. They expressed this in sentences like: "Conceptual modeling is just how we think!" The teachers have also indicated that the projects' quality is considerably higher and that the students show better understanding and more enthusiasm and self-confidence about their projects.

### 4.3 Roles for philosophers of science in educational practices

In the redesign of PjBL in this educational program, philosophers of science have made several contributions[18]:

- to articulate the discrepancy between educational ideas (based on constructivist learning theories) that form the basis for expectations about PjBL versus the actual (unsatisfactory) learning outcomes of this approach – thus creating awareness among teachers that this is a non-trivial, complex challenge in academic education,
- to clarify implicit philosophical presuppositions about what students are able to 'see' when entering scientific research – thus explaining why PjBL approaches often do not meet the expectations about the development of deep conceptual understanding and higher-order thinking skills (HOTS) and why scaffolds and well-prepared learning assistants are crucial to the development of HOTS in PjBL approaches,
- to propose a vocabulary in which the construction of scientific models is a significant scientific activity in practice-oriented scientific research,
- to promote *conceptual modeling*—rather than *applying science* and hypothesis testing— as an overarching learning objective that helps students develop scientific thinking,
- to design and implement scaffolds that support students' learning to (systematically) construct and reconstruct (scientifically-informed) conceptual models(e.g., the B&K method for constructing scientific models),
- to develop and teach a philosophy of science course to raise students' awareness of their 'pictures of science' and explain conceptual modeling as part of a possible alternative, and

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[17] Our philosophy of science teaching is focused on relevant aspects of constructivist epistemology. We thereby strive for students' understanding of scientific models, in particular, the philosophical understanding that scientific models cannot be literal representations of their target, and the importance of the role of conceptualization in the construction of models. Further details of this education are not covered in this article.

[18] In our example (Section 4), these contributions relate to the instructional design, the implementation, and the teaching of conceptual modeling in the project.

- to emphasize and explain the role of researchers' *epistemological responsibility*.[19]

In short, philosophers of science introduced a vocabulary into the educational practice that better reflects (constructivist) epistemologies of research practices concerning scientific methodologies, the 'logic' of constructing knowledge, the role of epistemic strategies, and researchers' responsibility in constructing new knowledge.

## 5 Concluding remarks

Concerning the limitations in developing deep conceptual understanding and higher-order thinking skills through project-based learning (PjBL) observed by teachers and reported in the educational literature, we have aimed to demonstrate that fundamental philosophical issues are at stake regarding the commonly used vocabularies (1) to think about education in scientific research, and (2) to talk *about* scientific research. As to the first point, the used vocabulary often reflects a traditional empiricist epistemology, including Aristotelian empiricism that neglects the crucial role of various instruments (technological, conceptual, mathematical) to 'create,' 'see,' 'describe,' and understand 'theoretical objects' (Matthews, 1993). When assuming that students will learn 'naturally' in PjBL approaches, 'the unnatural nature of science' (Wolpert, 1992) is overlooked. Regarding the second point, the vocabulary used to talk about science often reflects traditional empiricist epistemological views, which are too limited to understand actual scientific research practices. When teachers use this traditional philosophical vocabulary, it will convey an inadequate understanding of science to students.

Finally, with our programmatic contribution to this topical collection, we emphasize the importance of interdisciplinary collaborations between philosophers of science, educational researchers, and teachers. Philosophy of science in educational practices can help address the educational challenges outlined in this article by providing conceptual frameworks for understanding the character of scientific knowledge and research practices, including epistemologies that may form the basis for scaffolding (e.g., the B&K method, Boon, 2020b) to support students in their learning. In addition, the educational sciences provide advanced concepts and theories of how students develop an understanding of science.

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[19] *Epistemological responsibility* is a concept that focuses on epistemic agents and underlines that the epistemological tasks of experts and professionals —to gather, assess and integrate heterogeneous types of information and fit them into a model— involve a considerable amount of choice, deliberation, and justification, for which they should be held accountable (cf. Code, 1984, 1987). In our philosophical contributions to PjBL education, we aim to make students aware that, when systematically working along the lines of the so-called B&K method (Boon, 2020b), they bear epistemological responsibility for every choice and decision in the construction of a model. In this article, we will not elaborate on this notion but see Van Baalen and Boon (2015, 2017), Douglas (2000).

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