The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

Domain of Validity framework:

A new instructional theory for addressing students' preconceptions in science and engineering

Raoul Sommeillier[a], Kathleen M. Quinlan[b] and Frédéric Robert[a]

[a]Bio Electro and Mechanical Systems (BEAMS), Université libre de Bruxelles, Brussels, BELGIUM;
[b]Centre for the Study of Higher Education, University of Kent, Canterbury, UK

We propose a new instructional theory, the Domain of Validity (DoV) Framework, which offers a new way forward for designing teaching for conceptual change, while also resolving conflicts between existing theories related to common, difficult-to-change conceptions students have about particular scientific topics. We propose that knowledge consists of two connected elements: a model and a domain of validity (or DoV). Foregrounding the notion of DoV for given models allows us to reconceptualise and diagnose many problematic preconceptions as examples of an oversized DoV. Mapping the different elements of knowledge – both the model and its domain of validity – allows teachers to pinpoint precisely the cognitive conflict that students need to confront in a conceptual change approach to teaching. We highlight the instructional implications related to these scientific learning difficulties and conclude by proposing particular teaching strategies based on this new framework, emphasising the domains of validity of particular scientific models.

Keywords: misconception; conceptual change; science education; model-based learning; threshold concept

Introduction

Since the early 20th century, science education research has emphasised the importance of understanding students' prior knowledge (National Research Council, 1999; Rittle-Johnson, Star, & Durkin, 2009). Researchers from various backgrounds, periods and nationalities have studied how difficult-to-change prior knowledge impacts the way students learn, yielding a variety of terms and concepts that are similar, but have subtle distinctions. In this paper, we clarify existing constructs before proposing an integrative framework from which we derive instructional strategies that make explicit, rather than leave implicit, the domains of validity of given concepts.

First, we briefly summarise seminal ideas that address similar topics, have similar purposes, and contribute to an understanding of students' learning in sciences. The six constructs we review are: 1) misconceptions and preconceptions, 2) alternative and anchoring conceptions, 3) phenomenological primitives (p-prims), 4) threshold concepts, 5) cognitive obstacles and 6) conceptual change.

Second, we propose a new framework that builds on those key constructs, but explicitly attends to the context of application, or "domain of validity" (DoV) of a given model. This DoV framework makes explicit an aspect of existing theories that has remained largely implicit or overlooked. In doing so, it reconciles some of the tensions found between existing constructs and allows us to propose associated teaching strategies, which we emphasise in the last section.

Third, we reinterpret the constructs from existing literature in the new terms of our formalised DoV framework. This last step shows the coherence, limitations and contributions of the proposed framework in relation to the extant literature. Finally, we elaborate specific teaching strategies with examples to highlight the practical elements of the framework for enhancing teaching for conceptual change.

1. Literature Review

Research on "prior knowledge" is organised here into six constructs. Rather than an exhaustive review of research in the field, we examine the foundations of each of these constructs to point out their common ground and points of divergence. For each construct, we succinctly summarise its key features, the contributions it makes beyond previous literature, and major criticisms it has faced.

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

1.1. Misconceptions and Preconceptions

Since the 1960's, the science education literature has referred to students' conceptions under several names, including: *misconceptions* (Helm, 1980), *preconceptions* (Novak, 1977), *alternative conceptions* (Driver & Easley, 1978), *children's science* (Gilbert, Osborne, & Fensham, 1982), and *synthetic models* (Vosniadou, 2012). Some authors use other terms (e.g. *intuitive conceptions*, *naïve beliefs*, *pre-instructional conceptions*, *spontaneous knowledge*, *folk knowledge*, *personal models of reality*) to mean the same idea (Özmen, 2004; Peşman & Eryilmaz, 2010). The variety of terms in use today remains quite wide. Some authors justify their choice by explicitly defining the terms they use, but others do not.

The choice of terminology sometimes depends on the researcher's view of the status of knowledge (Gilbert and Watts, 1983) and on the semantics of the terms. For many authors (Demirci & Çirkinoglu, 2004) *preconception* and *misconception* refer to the same concept: a student's idea that is in conflict with scientifically accepted ideas (Gilbert & Watts, 1983; Viennot, 1985). For others, not all *preconceptions* are *misconceptions* (Brown & Clement, 1987; Clement, 1991, 1993; Clement, Brown, & Zietsman, 1989).

Some researchers do not characterise the relationship between preconceptions or misconceptions and scientifically accepted ideas in terms of conflict (Hammer, 1996; Hamza & Wickman, 2008; National Research Council, 2012b; Smith, diSessa, & Roschelle, 1994). For Driver and Easley (1978), the main property of a *preconception* is that it is naïve, immature, or under-developed compared to a scientific concept. A review of this literature (National Research Council, 2012b) uses the term *misconceptions* to mean understandings or explanations that differ from what is known to be scientifically correct, while recognising that some researchers refer to these

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

explanations as *alternate conceptions*, *prior understandings*, or *preconceptions*, and that the different terms can reflect different perspectives.

Other authors emphasise temporal aspect of these concepts. For Fetherstonhaugh and Treagust (1992), a *preconception* is simply a conception in a certain area that is present in the student's mind *prior to* relevant instruction (see also Subsection 1.2). Vosniadou (2012) reserves the term *misconception* for erroneous ideas that students still hold *after* instruction. And for Carey (1986), *misconceptions* may exist either *before or after* students have had relevant instruction.

The previous references demonstrate the variable meaning of these two first terms. The meaning of the most commonly used term, *misconception,* has evolved over time. According to the most common use of the term today, a *misconception* refers to ideas that differ from what is known to be scientifically correct (Hamza & Wickman, 2008; National Research Council, 2012b). Furthermore, *misconceptions* can be said (Hammer, 1996; Smith et al., 1994) to have four properties: a misconception (1) is knowledge that affects how students understand natural phenomena and scientific explanations, (2) involves stable (strongly held, difficult to change) cognitive structures, (3) differs from expert conceptions, and (4) must be eliminated or dismantled for a student to progress.

However, the third and fourth properties of misconceptions– an intrinsic incorrectness of the prior knowledge and consequent need for removal – have been questioned (Chi, 2008, 2013; Clement et al., 1989; Michelet, Adam, & Luengo, 2007). We incorporate these last two criticisms into our use of the term *preconception* to depict a more general and neutral concept than *misconception* (Brown & Clement, 1987; Clement, 1991, 1993; Clement et al., 1989). Thus, we define preconception as knowledge that has the two first properties mentioned above, but is mainly defined by

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

its presence before formal instruction (Fetherstonhaugh & Treagust, 1992) and by its role as an obstacle to further learning, without necessarily requiring dismantling (Chi, 2008, 2013; Clement et al., 1989; Gilbert & Watts, 1983; Michelet et al., 2007). Our definition then is: *preconceptions* (1) are knowledge affecting how students understand natural phenomena and scientific explanations, (2) are stable (strongly held, difficult to change) cognitive structures, (3) have been constructed by students (via experiences, formal learning, etc.) prior to the considered instruction and (4) can act as barriers to new learning. The review of constructs provides further elaboration for our broadened definition of preconceptions.

1.2. Alternative conceptions and anchoring conceptions

According to Gilbert & Watts (1983), researchers of *misconceptions* assumed that students' scientifically incorrect ideas were flaws in the knowledge base that needed to be eliminated or repaired for new knowledge acquisition to be successful. Yet, dismantling prior knowledge is inconsistent with constructivist views of learning (see discussion of Piaget in Subsection 1.5) that emphasise building on existing knowledge, which is seen as the product of an individual's intentional, active, and ongoing construction of meaning. Gilbert & Watts (1983) thought that students' scientifically "incorrect" ideas should be respected as "personally viable constructive alternatives" to scientific knowledge, thus preferring the terms *alternative frameworks* and *alternative conceptions,* after the work of Driver & Easley (1978).

Therefore, compared to *misconception*, which suggests via the prefix "*mis-"* an intrinsic incorrectness of the knowledge, *alternative conception* highlights the idea that students' prior knowledge (*preconceptions*) may be meaningful and useful in the learning journey. By the end of the 20th century, it was generally accepted that "prior knowledge can either interfere with or facilitate new learning" (National Research

Council, 1999). This early debate in the literature, though, helps accounts for the mix of terms for students' scientifically "incorrect" ideas in the education literature today. Many researchers continue to use the term misconception, but actually mean alternative conceptions. Insofar as they do not assume students hold an "inadequate 'picture'" of the world: "Students' alternative frameworks (frequently regarded as misconceptions) play a crucial role in science concept learning" (Nussbaum & Novick, 1982, p. 183). Teaching to overcome inappropriate alternative conceptions "could mean modify the domain of, displace, modify and improve, replace, or suppress a conception, depending on what is most appropriate" (Clement, 1993, p. 1242).

Clement and colleagues (Brown & Clement, 1987; Clement, 1991; Clement et al., 1989; Hammer, 2000) insisted further on the positive facet of some preconceptions. Their research led to the notion of *anchoring conceptions*: "Although many preconceptions are detrimental to learning, some are largely in agreement with accepted physical theory. These will be referred to here as "anchoring conceptions" (or more briefly, as anchors)." (Clement et al., 1989). Based on their studies, Clement et al. (1989) observed that students' correct answers to a particular example can trigger an *anchoring conception* that is a starting point for building an expert-like conception.

Clement (1993) reported success in using a teaching approach in mechanics that extended students' physical intuitions from an *anchoring example* (e.g. a spring) to the misunderstood example (e.g., the "springiness" of molecules in a seemingly rigid table) through a series of carefully sequenced, intermediate examples. The key relationship or structure (e.g. springiness) is the major relationship in the situation that the student needs to transfer to other situations.

1.3. Phenomenological primitives (or p-prims)

DiSessa distinguished two views in the literature. The first, what he called the *conceptual framework* view, includes the constructs of *misconceptions*, *alternative frameworks* and *naïve conceptions* because they all: (1) regard students' ideas to be fully formed, stable, and connected (diSessa, 2014; Hammer, 1996; Taber, 2008); (2) emphasise the differences between novice and expert knowledge (Smith et al., 1994); and (3) must be challenged (Taber, 2008), eliminated or overcome (Hammer, 1996) in order for students to develop scientific understanding.

In contrast, diSessa proposed a new perspective he called the *knowledge in pieces* view. Firstly, he argued that students' thoughts may not be stable, theory-like, content-dependent, stored knowledge structures. Instead, they may be spontaneous, transient, context-dependent constructions that arise from the activation of small, intuitive, and more fundamental knowledge elements to deal with an immediate situation. They arise in the moment, without students having thought about it consciously before. He called these abstract fragmentary knowledge structures *phenomenological primitives* or *p-prims* (diSessa, 1986, 1993; Hammer, 1996; Smith et al., 1994). Thus, diSessa questioned the first and second properties of *misconceptions/preconceptions* in the definition above (Subsection 1.1).

For example, when students are asked why it is hotter in the summer than the winter, they will often explain that it is because the Earth is closer to the sun (Sadler, Schneps, & Woll, 1989). From a *conceptual framework* view, this explanation is part of a coherent structure of knowledge about the solar system. From a *knowledge in pieces* perspective, the students constructed that explanation in the moment based on the fragment of knowledge that moving closer to the sun would make the Earth hotter. Thus, students activated the p-prim connecting proximity and intensity: “closer means stronger”. Other p-prims have been identified by diSessa (1993) including "maintaining agency", "actuating agency", and "dying away". Like "closer means stronger", they are not incorrect in and of themselves, but their activation in certain contexts is inappropriate.

Secondly, this new *knowledge in pieces* view challenged another aspect of the *conceptual framework* view: its perception of the discontinuity between naïve and expert knowledge (Smith et al., 1994). By studying physics experts' thinking as well as novices' thinking, they showed that intuitive ideas were still present in expert knowledge (diSessa, 1993; Smith et al., 1994). Instead of naïve thinking and expert thinking being completely different, the *knowledge in pieces* view held that learning at all levels was a process of reorganising intuitive ideas into better knowledge (diSessa, 1993; Hammer, 1996; Smith et al., 1994).

1.4. Threshold concept

More recently, Meyer and Land coined the term *threshold concept* which has been widely applied in higher education research, but not at other educational levels (Cousin, 2006a; Land & Meyer, 2006; Meyer & Land, 2003; Meyer, Land, & Baillie, 2010). Their thinking was influenced by David Perkins' *troublesome knowledge* (Perkins, 1999, 2006), which shifts the focus from students' cognitive constructions to the nature of the knowledge itself. Thus, instead of locating the problem of understanding in the student, it situates the problem as a property of the knowledge itself.

They formulated key features of threshold concepts (Cousin, 2006a; Cullen, 2010; Land, Cousin, Meyer, & Davies, 2005), though these have not been well-debated or differentiated in the literature (Quinlan, Male, Baillie, & Stamboulis, 2013). We focus here on transformativeness, integrativeness, boundedness and troublesomeness as key features, and on what they called the "state of liminality".

A threshold concept is *transformative* in that, once understood, students experience a significant shift in the perception of a subject and often of themselves. For

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

example, biological variation has been proposed as a threshold to understanding evolution (Batzli, Knight, Hartley, Maskiewicz, & Desy, 2016). Variation is needed for natural selection to take place; appreciating its role allows students to understand the randomness of evolutionary change, shifting their view of biology and their own place in nature. Thus, Meyer and Land (2003) add assumptions about the transformative nature of certain key concepts. *Misconceptions*, *alternative conceptions* and *p-prims* may be difficult to alter and common, but no claims are made about the importance of those prior conceptions or the centrality of them to progressing in the discipline. By emphasising the transformative nature of thresholds, Meyer and Land give them special curricular significance.

A threshold concept is also *integrative* insofar as it exposes the previously hidden interrelatedness and connections with other concepts or parts of the discipline. Thus, their integrative nature is another notable feature not claimed by other traditions reviewed earlier. This property of "integrativeness" is now emphasised more in recent research on *conceptual change*, notably in the *framework theory approach* developed by Vosniadou and her colleagues (2008) (see Subsection 1.5).

A threshold concept is often, though not always, *bounded*, in that any conceptual space will have terminal frontiers, bordering with thresholds into new conceptual areas. It might be that such boundedness serves to demarcate different disciplinary areas (Meyer & Land, 2003).

Finally, a threshold concept is also likely to be *troublesome*, involving "troublesome knowledge": "different kinds of knowledge – inert, ritual, conceptually difficult, and foreign – are likely to prove troublesome for learners in different ways" (Perkins, 1999, p. 8), they can also be tacit or using troublesome language (Meyer &

Land, 2003) or troublesome due to fear of uncertainty (Baillie & Johnson, 2008, pp. 137–138)

These authors also suggest that the process of learning a threshold concept involves an in-between unstable state in which the students oscillate between earlier and emergent understandings (Land & Meyer, 2006). They called this the state of *liminality*, referring to work by Brousseau (1989a) on *epistemological obstacles* (see Subsection 1.5).

Threshold concepts are described differently than the constructs reviewed above insofar as the *threshold concept* is the targeted concept to be understood, rather than the prior knowledge relative to it. Moreover, this theory discusses both the nature of knowledge and the process of acquiring new knowledge without making a clear distinction between these two foci.

In other words, this area of research is more focused on identifying the steps and the result of a process necessary to grasp the threshold than on entering the minds of the students' as learners to understand their prior knowledge of this threshold. It is, therefore, more focused on the structure of the discipline, curriculum and course design than the cognitive structures or reasoning processes of individual learners (Cousin, 2006a). This shift in focus is a key step in building our own theory of DoVs because it prompts us to consider the structure of knowledge itself.

Their discussions of liminality also (Land et al., 2005) add insights about the learning process and implications for teaching. They argue that teachers need to support students through liminal states, trusting that their students can tolerate confusion. The learning process is *recursive and excursive*: there is no simplistic, linear, learning approach from easy to difficult. The mastery of a threshold often involves many "takes" and looping back on the material (Cousin, 2006a).

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

1.5. Cognitive obstacles

The francophone educational literature from earlier in the 20th century also addressed many of the same issues as the later – mostly Anglo-American – literature discussed above. Constructivism is generally associated with Piaget research during the 1920-30's. In Piaget's view, learning is based on the interactions between the prior cognitive structures (or *schemes*) of learners and their environment (Piaget, 1967).

In parallel, Bachelard (1938) introduced the idea that students' mistakes are evidence of knowledge, arguing that the process of awareness of a contradiction and then overcoming it is the driving force of learning. Didactics has later articulated these two views:

> "The mistake is not merely the effect of ignorance, uncertainty, or happenstance, as is assumed in empirical or behaviourist theories of learning, but the effect of prior knowledge that had its role, but now is shown to be false or simply inappropriate." (Brousseau, 1983)

From these fundamentals, some authors attempted to define *obstacle*. For instance, Fabre (1995) and Astolfi (2006) elaborated six key features: inwardness, ease, positivity, ambiguity, polymorphy, and recursiveness (translated from French by the authors[1]). While the first three features are a part of the previous constructs reviewed here, we focus on the last three because they bring different contributions that we build on in our proposed theory.

According to Brousseau (1989b, 1989a), an obstacle has *ambiguity* because it can be either functional or blocking, depending upon its context. Knowledge in some contexts, provides suitable solutions to problems, but outside of those contexts, leads to

---

[1] Terms translated by the authors from the French corresponding terms: "intériorité", "facilité", "positivité", "ambiguïté", "polymorphie" and "récursivité".

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

errors. This *ambiguity* explains why some knowledge may resist instruction and continues to be mobilised by learners. In other words, the knowledge has proven to be correct and useful in some (but not all) situations, making it useful to retain. Although the concept of *ambiguity* is consistent with arguments for the value of some preconceptions, as discussed under Subsection 1.2 above, it highlights the context of use of a given concept, an element we foreground in our DoV framework.

Polymorphy means that an explanation system rooted in a deep and coherent network of ideas may manifest in different forms in seemingly unrelated situations. Thus, polymorphy resembles the integrative property of the *threshold concept*. Polymorphy also means that the cognitive obstacles may be in relationship with multiple other dimensions: motivational, affective, emotive, etc. Even if regularly mentioned in the literature, those aspects have received less attention than cognitive ones (see, as exceptions, Pintrich, Marx and Boyle (1993); Tyson, Venville, Harrison and Treagust (1997); Zembylas (2005)) We pick up on these emotional aspects in our own theory, insofar as teachers need to be mindful of them.

Recursiveness means that an obstacle is perceived as such only by people who can link the prior conceptions to refuting knowledge. So, an error can be identified as an obstacle only after having overcome this obstacle, thus highlighting the relationship between the obstacles and a metacognitive loop back on learning. Given this definition and as the term “recursive” is used with changes in meaning in different constructs (including our DoV framework), we refer to this feature as *retrospection* rather than recursiveness.

This *cognitive obstacle* perspective opened the doors to much science education research. For instance, research about students’ reasoning highlighted cross-cutting regularities of obstacles such as *spontaneous reasoning* in elementary dynamics

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

(Viennot, 1979, 1985), *sequential reasoning* in electrokinetics (Closset, 1983), and *causal linear reasoning* in thermodynamics (Rozier, 1988), as well as the theory of *conceptual fields* of Vergnaud (1994, 2009), or the notion of *goal-obstacle* of (Martinand, 1995). This construct also laid the foundations for more recent, elaborated and learning process-oriented theories related to the next construct: the theory of conceptual change (Subsection 1.6).

Early constructivism (Piaget, 1967) viewed learning as the result of a dynamic process tending toward equilibrium between the learner and his environment. It rested upon two complementary processes: *assimilation* and *accommodation*. *Assimilation* is the integration of new information into the cognitive structure of the learner without modifying the learner's cognitive structure. An *accommodation* occurs when the external situation drives a change in the learner's cognitive structure to accommodate the new information.

According to Piaget, an *accommodation* mechanism can take place if, previously, an attempt at *assimilation* has failed and if the resistance creates disturbance in the learner's mind. This unstable state is called *cognitive conflict*. These kinds of conflicts may lead to a *cognitive rupture*; in the face of disturbances, the learner may switch from one set of representations to another. Other authors have refined how this process takes place (Posner, Strike, Hewson, & Gertzog, 1982; Strike & Posner, 1985).

Bachelard (1938) – and later, in mathematics, Brousseau (1983) – went beyond giving these learning obstacles the status of knowledge. For him, some of this knowledge is essential to learning students have to temporarily learn "false" knowledge because the awareness of this erroneous aspect would be constitutive to the construction of the target knowledge. He called these unavoidable obstacles that act as steppingstones to more sophisticated knowledge *epistemological obstacles*.

According to the *cognitive obstacle* perspective, a problem in classical learning processes is that the teacher focuses on the target knowledge and sees students' representations (the obstacles) as a barrier to acquiring the target knowledge. For students, though, these pre-existing representations are valuable intellectual tools to be used as long as they work.

1.6. Theory of conceptual change

The constructs in Subsections 1.1, 1.2 and 1.3 mainly focused on the nature of the student's knowledge. With the *threshold concept* and the *cognitive obstacle* (Subsections 1.4 and 1.5) perspectives, the focus shifted to the *process* by which learners evolve from one set of concepts to another. This process was formalised by Posner, Strike and colleagues under the name *conceptual change* (Posner et al., 1982; Strike & Posner, 1985).

Starting from a Piagetian position that learning is a rational activity, Posner et al. (1982) were concerned with "how students' conceptions change under the impact of new ideas and new evidence." They drew a parallel between, respectively, assimilation and accommodation processes and the "normal science" and "scientific revolution" phases developed by well-known philosophers of science (Kuhn, 1970; Lakatos, 1978). Posner and colleagues (1982) focused their research on *accommodation*.

Posner's theory of accommodation (Posner et al., 1982) proposed four conditions of accommodation: (1) the existing conception (prior knowledge) must be dissatisfying, (2) the new one must be intelligible, (3) plausible, and (4) fruitful (i.e. it should have the potential to be extended). They define a student's conceptual ecology as the existing concepts that will influence the selection of a new central concept. Two kinds of concepts are particularly important determinants of the direction of an accommodation: anomalies and fundamental assumptions about science and knowledge.

Posner's approach to replacing prior knowledge with scientifically acceptable knowledge – now called the *classical conceptual change approach* – became the leading paradigm in science education. But it was progressively subject to criticism, including that it offered a simplistic view of misconceptions with no relation to other concepts, the context, or motivational, emotional and affective dimensions (Caravita & Halldén, 1994; Zembylas, 2005) and ignored students' productive ideas (Smith et al., 1994).

Taking these criticisms into account, Vosniadou and colleagues (Vosniadou, 2006; 2007) have developed a re-framed conceptual change approach to learning: the *framework theory approach.* This theory, as well as the *Synthetic Models Approach* (Vosniadou, 2012), is constructivist and sees misconceptions as part of a knowledge system consisting of many different elements organised in complex ways built through successive (conflicting) assimilations, that is, gradual change rather than sudden restructuring. While cognitive in focus, it is not incompatible with affective, motivational or socio-cultural factors (Vosniadou, 2006).

2. Why a new theory is needed

From the preceding review, we see that there is a number of unresolved issues between science education concepts that explain students' difficult-to-change conceptions. In sum, the constructs vary in terms of whether they see prior knowledge as intrinsically incorrect and in need of removal or as positive and useful; whether they see transformation as continuous or discontinuous; the degree of recursiveness; and even the stability of prior knowledge.

In particular, we note many constructs seem to "circle around" the notion of the "context of application" of students' conceptions rather than placing it at the centre of their theories. This notion has been mentioned, but not elaborated, in *anchoring*

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

conceptions, *p-prims* and *cognitive obstacle* constructs. There is also a link between this idea and the "boundedness" feature of the *threshold concept* construct.

Hence, one motivation for an additional theory is to reconcile points of divergence between the abovementioned constructs. As we'll detail in Section 3, the first hypothesis of our theoretical proposal is that this "context of application" – or what we call the "domain of validity" (DoV) – is an essential part of the individual's knowledge. This proposition resolves some of the conflicts cited above (see Section 4).

However, our main motivation and contribution lies in the operational power of our framework to "map" the nature of obstacles to learning and to directly infer from this map a practical teaching strategy. This power relies on the second hypothesis of our framework, that explicitly defines preconceptions as an overgeneralisation of the DoV. To explain why this is a significant shift in perspective, we discuss briefly the instructional power of previous constructs.

The existing theories mainly have an explanatory value and are not intended to be theories of instruction. On one level, all of these perspectives have similar instructional implications: they see students' incorrect statements as reflecting (shared) cognitive structures rather than as individual, nonsensical mistakes (Bachelard, 1938). Thus, they suggest it is important for an instructor to explore students' misunderstandings, uncertainties and prior knowledge and to look for the sense behind students' incorrect statements.

However, there is less consensus on teachers' actions after this "diagnostic" phase. Moreover, the links between the teaching implications and the key features of the learning difficulties described in each construct are rarely straightforward. Viewing student's conceptions as inherently incorrect prompts attempts to remove, dismantle or replace in contrast to reorganising students' existing understanding or intuitions

(Clement et al., 1989; diSessa, 1993; Hammer, 1996; Smith et al., 1994). Exploiting prior knowledge as resources for new learning can take different shapes, though. On the one hand, the teacher could choose to recognise students' preconceptions as a creative and productive act of meaning-making and then use these acts of reasoning as steps toward more expert-like understanding. On the other hand, the teacher may create a set of conditions conducive to supporting students through cognitive conflicts (or liminal states), by making a new conception more intelligible and plausible (Posner et al., 1982; Strike & Posner, 1985), by tolerating learner confusion (Cousin, 2006a), by using teaching techniques such as metaphors and analogies (Clement, 1993), by changing the semiotic representations (Duval, 1993), by creating socio-cognitive conflicts in class (Brousseau, 1989b; Closset, 1992), or sometimes by acting as an adversary confronting the students when they attempt problematic assimilations (McDermott, 2005; White & Gunstone, 2014).

In this paper, we privilege the practical challenges of teaching and argue that moving the domain of application to the foreground (and the model, to some extent, to the background) is the critical shift in perspective proposed in our framework. Two of us are engineers, which may explain the different focus we promote here. The job of scientists is to create models and theories that describe the world and then demonstrate the generalisability of those theories (that is, ever-wider domains of applicability). Thus the model is central. The job of professional engineers, or applied scientists, is to solve (sometimes very complex) problems. To do so, they focus first on understanding the context of application, before selecting among various available models, a process called "modelling the problem" (Quinlan et al., 2012). Engineers are constantly assessing the trade-offs between complexity (accuracy) and efficiency as they apply to the demands of a given situation. For example, to design a power supply, why would an engineer use a thousand-equation model if a ten-equation model is much faster to compute and provides the same mathematical result within 1% accuracy? The ten-equation model may be applicable to fewer situations (less generalizable, less complex), but still useful, convenient and efficient for this specific situation. In this example, it is important to note that the choice of models is not the choice between models used in the everyday lifeworld versus the symbolic domain (Solomon, 1983), but between two or more models used in the symbolic domain.

We bring this way of “thinking like an engineer” (Quinlan et al., 2012) to problems of teaching and to the analysis of students’ errors. First, in analysing students’ errors, we saw how they were related to students’ choice of symbolic models (rather than Solomon’s (1983) everyday vs symbolic models). We saw that their errors were a problem of applicability to a given situation, rather than a problem with the model itself. In reviewing the literature on students’ preconceptions, we saw a tendency to focus primarily on the model (preconception) itself, rather than its domain of validity.

Second, we sought not only to describe students’ understandings, but to solve a practical, instructional problem. That is, our theory is focused on deriving teaching strategies. Our proposal is not intrinsically “better” than the ones proposed before, but it is more oriented towards building teaching strategies, as we’ll illustrate in Section 5. Our theory directs teachers’ attention to the “paradoxical experience”, as well as offering a unique graphical representation of the cognitive shift required, which has not previously been documented.

In summary, we claim that our proposal, by foregrounding the “domain of validity” as an essential part of individual’s knowledge itself (first hypothesis), explains the nature of preconceptions more explicitly and operationally than previous constructs (second hypothesis). The increased operationality comes from making the domain of

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

validity central, rather than secondary, when elaborating teaching strategies intended to overcome preconceptions. And we believe this shift in the gaze for teachers, students and even researchers, offers a novel contribution to the literature that builds on, rather than contradicts, earlier references to applicability of models (e.g. context sensitivity in the knowledge-in-piece perspective (Hammer, 1996), lifeworld vs symbolic models (Solomon, 1983), learning impediments (Taber, 2001, 2008), framework theories (Vosniadou, 2012), constructive alternativism and range corollary of the Kelly's personal construct theory (Fransella, 2003; Kelly, 2005) or contextual effects on students' reasoning (Palmer, 1997)).

While science teachers may agree with the principle of teaching the range of applications of models, this may not be happening in practice. For example, in chemistry, Drechsler and Schmidt (2005) showed that textbooks often illustrate models of acids and bases in successive order, but fail to draw connections between them or explain how, under differing circumstances, one model may be better than another. Furthermore, they found that teachers rarely explicitly taught models and frequently did not understand the differences between two of the most common models.

When models are taught, they may be taught from a science, rather than an engineering perspective. That is, the focus may be on the generalisability of models – that is, expanding the domain of validity – rather than on shrinking it or testing it for its utility (alongside other candidate symbolic models) in a given situation. This emphasis on expanding the domain of validity is consistent with the much more commonly understood challenge of transfer (Salomon & Perkins, 1989). Thus, we argue that neither teachers nor researchers are routinely describing preconceptions as a problem of an *overgeneralised* domain of validity. Nor are teachers routinely using an instructional sequence designed to trigger the process of *downsizing* a domain of validity. Our theory, while not the first to acknowledge domains of validity, nevertheless makes a significant contribution to science education.

Finally, in addition to its operational power, our proposal also resolves discrepancies between existing constructs. These are the elements we will now develop in more detail. In Section 3, we elaborate the concept of "domain of validity" at the heart of our DoV framework. In Section 4, we show how our theory of DoV reconciles discrepancies across the constructs reviewed above. Based on the DoV framework, we present a teaching strategy that we have developed and trialled which involves the creation of paradoxical situations. This strategy is explained in Section 5, along with examples highlighting DoV-centric teaching strategies.

3. Domain of Validity framework

We present in this section a proposal for a conceptual framework whose core element is the notion of *domain of validity* (DoV): the DoV framework. The origin of this framework is our study of the processes occurring during courses in an engineering school at university level when teachers confront students' learning difficulties apparently caused by prior knowledge. This approach prompted us to model the observed phenomenon and derive an explicit teaching strategy to address these difficulties.

Given the aims of this formalised tool (mainly helping teachers to identify students' preconceptions and to develop effective, theory-based teaching strategies), this DoV framework is compatible with most of the concepts cited in Section 1 and reconciles some of the oppositions noted in Section 2.

As any model[2], it does not pretend to address all aspects of learning. After presenting and illustrating this DoV framework (based on two main hypotheses), we discuss its links with existing literature.

3.1. A first hypothesis about knowledge: K=M+DoV

As seen in the review in Section 1, in existing constructs, the *knowledge, conception* or *model* is typically considered to be the central (if not sole) element to be learned. That is, the knowledge and the model are treated as the same thing. Discussion across the various constructs then tends to centre on how compatible that knowledge (conception or model) is in relation to expert views. Instead, we hypothesise that a person's knowledge consists of *two* connected elements: a *model* and a *domain of validity* (or *DoV*).

A model is a tool that allows its user to economically understand, describe and predict real world behaviour using abstraction. The American Framework for K-12 Science Education (2012a) defines conceptual models as "explicit representations that are in some ways analogous to the phenomena they represent" which "allow scientists and engineers to better visualize and understand a phenomenon under investigation or develop a possible solution to a design problem" and "include diagrams, physical replicas, mathematical representations, analogies, and computer simulations" (National Research Council, 2012a, p. 56).

Whatever the type, all models contain approximations and assumptions (Halloun, 2011; National Research Council, 2012a). Confronted with their environment ("*experiences*"), humans need a way to reduce its complexity or *abstract* it. Thus, knowledge involves generalisation: creating a set of concepts and links between those

[2] The term "model" is used here in accordance with the definition given in Subsection 3.1.

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

that extract and formalise some regularity across individual situations, so we can communicate and reason about the world around us. In science and engineering, these generalisations take the form of concepts, principles (links between concepts, that may typically appear as equations), procedures or (meta)cognitive strategies (Anderson (Ed.) et al., 2001; Krathwohl, 2002). A few examples will be given in the coming sections.

In addition to a model, we argue that "knowledge" contains a second key element: the *domain of validity* (or *DoV*). The DoV is the bounded area within which the *model* properly describes real-life experiences. It guides the *selection of* a specific model when facing a specific situation.

One advantage of this definition is its ease of visual formalisation, statically as well as dynamically. 1 illustrates this view: a piece of knowledge (whole figure) is the association of a model M1 and a domain of validity DoV^1 (represented by the rounded-corner box). The dots represent various experiences: these include situations students may face in everyday life (observations, experiments, phenomena, etc.) as well as situations created by the teacher (e.g. exercises, labs, problems, etc.). Some of the dots are inside DoV^1 (white dots), while others are outside DoV^1 (black dot): M1 properly describes the three "white-dot" experiences, but not the "black-dot" experience.

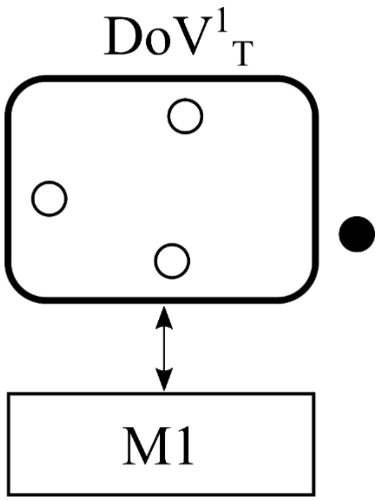

Figure 1. In the DoV framework, knowledge is the combination of a model and a domain of validity (DoV)

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

We assume the DoV is also built by generalisation. However, we hypothesise that the DoV is more implicit and unconscious than the model itself. The implicitness of the DoV is illustrated in the review of constructs in Section 1, in which the *model* is usually considered equivalent to *knowledge*. As pointed out in the review, Clement (1993) is an exception when he notes that modifying the domain of a conception is an option. Brousseau's (1983, 1989a, 1989b) "ambiguity" takes us much farther in explicitly recognising that concepts may be appropriate in some contexts and not others. Hammer (1996) stated that "context sensitivity is easier to understand from a p-prims perspective than it is to understand from a misconceptions perspective". And the "boundedness" of threshold concepts (Cousin, 2006a; Cullen, 2010; Land et al., 2005) also points us toward considering the boundaries of a concept, but research in that tradition has not emphasised that feature.

Our first hypothesis has two important consequences[3]. Firstly, a model – assuming it reproduces or explains at least one experience from the perspective of its owner – cannot be intrinsically false because it successfully describes something in the surrounding world. Thus, once a model allows us to predict what will happen in some situations (DoVs), it can be considered "valid". Focusing on the DoV, then, allows us to depart from characterising models as "right or wrong" or even "naïve or expert", as much of the literature discussed in Section 1 does (Clement et al., 1989; Gilbert & Watts, 1983; Smith et al., 1994).

For example, in engineering, Maxwell equations (model) represent very well an extremely large set of experiences of electromagnetic phenomena ("white dots"), but they do not represent the electrochemical reaction that occurs in a battery to produce the

[3] For these consequences, we do not need to assume that the DoV exists inside individuals' minds, so the following considerations may be thought of as outside of individuals.

electromotive force (“black dot”), which is, however, a very common element in electrical circuits. Hence saying that Maxwell equations are either “right” or “wrong” is a poor description of their validity. They are “right” in situations within their DoV, but not outside it.

The second consequence of our hypothesis that knowledge contains two interrelated components (*model* and *domain of validity*) is that different models are not mutually exclusive. There is no single “right” model surrounded by “false” models; models just coexist, having different DoVs. Moreover, depending on the context, different models offering different levels of precision can be used to describe the same experience. For example, the full Maxwell equations can coexist without contradiction with a simplified set of quasi-static equations in which propagation effects do not exist, and even with a third model where individual electric charges simply attract or repel themselves depending on their distance and their electric charges. “Experts” may use any of them given the level of specificity they seek.

For an example from everyday life, the model of the Earth as flat is extremely useful and highly accurate when building a house, but disastrously inaccurate when launching a satellite. Another well-known example is the coexistence of classical mechanics (Newton) and the theory of relativity (Einstein).

Introducing the DoV concept allows us to capture the fact that a model is sufficient in many but not all circumstances. This point is depicted at the top of 2 (representing the teacher’s cognitive structure) where two models M1 and M2 are both valid but in different domains of validity.

This two-component perspective invalidates the idea of “wrong” knowledge (in the sense where the model is wrong) in many situations. Coming back to the modelling of Earth, “the Earth is flat” contradicts scientific understanding. However, as we pointed

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

out, this model is sufficiently "true" to build a house. The contradiction doesn't come from the model itself, but from the failure to recognise and discuss models together with their associated domains of validity. So, our shift consists in replacing the "true/false" character of a model with a much more nuanced concept: the domain of validity. This brings us back to the idea of alternative conceptions (Subsection 1.2), with the nuance that we clarify that the "correctness" of a model depends upon being *inside* its DoV.

These ideas are aligned with other constructs (Hammer, 1996; Palmer, 1997; Smith et al., 1994; Taber, 2008) but we claim that this formulation, emphasing the context-sensitivity of knowledge, offers a powerful tool for teachers. Ultimately, this formulation should help teachers understand how to teach models and modelling, important over-arching concepts in science (Halloun, 2006; National Research Council, 2012a). As we'll see, emphasising the domain of validity as a part of the knowledge itself, on equal footing with its associated model, opens new paths in terms of teaching. In effect, we are suggesting taking an engineering perspective, rather than a scientific perspective, on the teaching of models and modelling.

In summary, the DoV is the (often implicit) part of the cognitive structure that describes the area within which a model succeeds in describing and predicting real-world behaviour. DoVs lead us to abandon the idea that a conception is "right" or "wrong" and opens the door to multiple valid conceptions coexisting. Thus, even if researchers and teachers agree that "all models contain approximations and assumptions that limit the range of validity of their application and the precision of their predictive power" (National Research Council, 2012a, p. 56), explicit formalisation and recognition of the importance of domains of validity is lacking in existing literature and teaching practices.

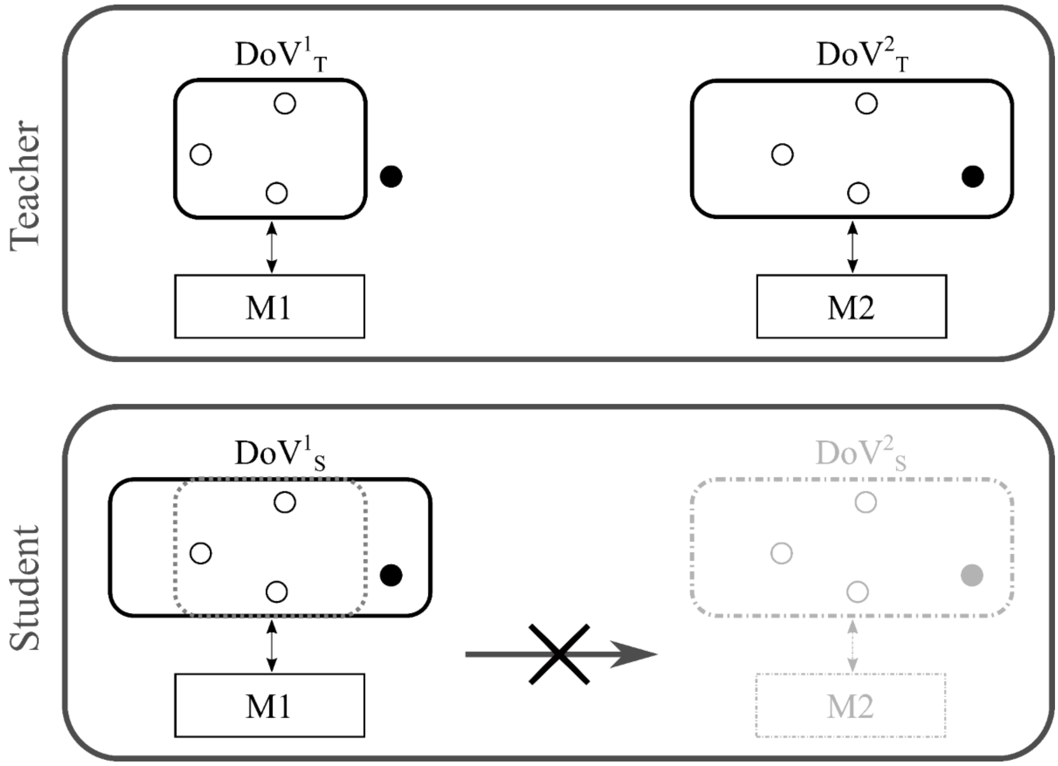

Figure 2. Graphical formalisation of the DoV framework applied to a simple teaching situation

3.2. A second hypothesis about preconceptions: P=M+ODoV

The second proposition of the DoV framework is that the very nature of some preconceptions is an *overgeneralised domain of validity (ODoV)*: a domain of validity too wide relative to what the associated model can really represent (Figure 3). Believing that "the Earth is flat in all circumstances" is an overgeneralisation from everyday experiences of the domain of validity of this model: it serves us in the situation of housebuilding, but not when putting a satellite into orbit. This simple hypothesis explains many phenomena related to prior knowledge. It also suggests that the typical blocking situation experienced in learning may arise when either the teacher or the student focuses only on the model (without its associated domain). Although this basic example focuses on the difference between lifeworld (everyday) and symbolic (scientific) models (Solomon, 1983) for ease of reading, problematic preconceptions also arise when one scientific/symbolic model is applied in place of another scientific/symbolic model.

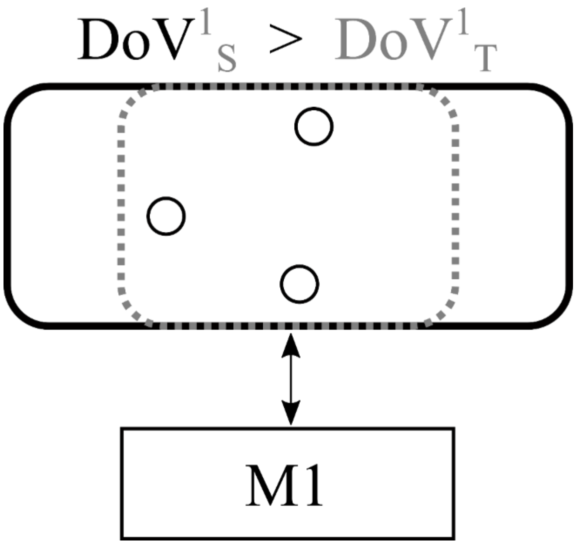

Figure 3. In the DoV framework, a preconception is a knowledge consisting of the combination of a model and an overgeneralised domain of validity (ODoV)

For instance, the different atomic models taught in middle and high schools (generally Ancient Greek model, Dalton's, Thomson's, Rutherford's and Bohr's models) are numerous (Cokelez & Dumon, 2005; Justi & Gilbert, 2000) and each can be considered as valid to some extent. The Ancient Greek model (or ball model) is relevant to understand and teach that matter is not "continuous and infinitely divisible" but "composed of very small indivisible corpuscles" (Justi & Gilbert, 2000). But this model offers no basis for distinguishing between types of atom (a contribution from Dalton) and it obviously cannot explain the internal structure of atoms (electrons (Thomson) and nucleus consisting of protons and neutrons (Rutherford), the former orbiting the latter (Bohr)). Hence, the domain of validity of the Ancient Greek atomic model doesn't include isotopes or chemical bonds (Özmen, 2004; Taber, 2005). Believing that molecules are groups of ball model atoms is, in the DoV framework, due to a preconception consisting of an overgeneralised domain for the Ancient Greek atomic model.

Other examples of symbolic models with varying DoVs include the Maxwell equations mentioned earlier, Newtonian physics versus relativity or the different definitions of acids and bases (Drechsler & Schmidt, 2005; Taber, 2008).

Returning to the cognitive structure depicted on the top half of Figure 2, this teacher has two models in mind, with different DoVs, both coexisting without contradiction. One experience (black dot) is properly described by M2 but not by M1. For instance, electromagnetic propagation effects are properly described by full Maxwell equations (M2) but not by the quasi-static ones (M1), the launch into orbit of a satellite can be properly described on a spherical Earth (M2) but not on a flat Earth (M1). We will follow this last basic example throughout the next explanation to make it more explicit.

The bottom part of Figure 2 depicts the cognitive structure of students who are likely to possess a preconception related to M1: the students possess the same model M1 as the teacher but associated with an ODoV (here including the “black dot” experience covered by M2)[4]. According to our theory, the difference in DoVs associated to M1 between the teacher and the student may explain many phenomena described as problematic preconceptions.

---

[4] The existence of this cognitive structure is consistent with the ideas that (1) humans tends to generalise their experiences in order to find some regularity and (2) the DoV is more implicit than the model itself. Indeed, such a cognitive structure could, for example, result from the following situation: (1) The teacher, having presented “white dot” experiences to the student (including exercises in class, for example), has always told students they were “right” when giving correct answers using M1; (2) the student has not been exposed to the “black-dot” experience yet; (3) the student, by generalising these white dot experiences, implicitly builds an overgeneralised DoV of M1 since neither the student nor the teacher consider knowledge as having any component other than the model itself.

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

Starting from the situation depicted in Figure 2, when the teacher presents the students with a "black dot" experience (satellite launching) for the first time (for which M2 is a better fit), the students will use M1 (flat Earth) according to their own cognitive structure, especially if the student is not conscious of a structural difference between this black-dot experience and the white-dot experiences (basically, a difference in scales). Thus, the student is confident in M1 because using it in the past has resulted in positive feedback from the teacher or everyday life. In a classical teaching situation focused only on models, the student's answer will be considered "wrong" because it does not include M2 (round Earth) as the teacher expects ("Earth is not flat, it's round!")[5].

For students focused only on the model without awareness of DoVs, the first encounter with the black-dot experience (satellite launching) will result in three simultaneous discordances:

1. At a cognitive level it is difficult to understand, in absence of additional elements, *why* M1 (flat Earth) suddenly "does not work" when it has always worked before. This can be linked to the *ambiguity* of the cognitive obstacle (Astolfi, 2006; Brousseau, 1989b, 1989a; Fabre, 1995) and to the troublesome aspect of the threshold concept (Meyer & Land, 2003; Perkins, 1999).
2. At an affective/emotional level, it may be upsetting when the model M1 in which a student has confidence built on past experiences (e.g. housebuilding) suddenly doesn't work anymore. Students may feel a sense of betrayal,

[5] It is worth noting that, scientifically speaking, the planet Earth is neither flat nor round. Using the round Earth model (M2) without taking on board its domain of application (for instance by considering this model as appropriate for any context) may consist in a new preconception. Therein lies the recursive aspect of learning in the DoV framework.

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

especially when a pattern of positive teacher feedback for use of M1 is broken. Insofar, considering such a model as an individual's representation of the world, if the distinction between the model and the world is unclear in the student's mind, modifying the model would mean, disturbingly, modifying the world itself! This affective aspect can be linked to the emotional discordance highlighted in the *thresholds* literature (Meyer et al., 2010; Schwartzman, 2010) and to the affective aspects in the *conceptual change* literature (Duit, Treagust, & Widodo, 2013; Tyson et al., 1997; Zembylas, 2005).

3. At an epistemological level, it is difficult to understand why one should throw away a model that works in practice. This epistemic aspect can be linked to the works of Piaget (1967), Bachelard (1938) and Posner et al. (1982).

We call the black-dot situation a *paradoxical experience* for two reasons, which both include a paradox:

1. A paradox common to all situations: in the absence of additional explanation (as, for example, that M2 could be a superset of M1), "abandoning" M1 is paradoxical because it worked well up to that moment.
2. A paradox specific to the situation: the black-dot experience is the very element that will create an incongruity in student's mind, in relation to the content of the targeted preconception. Hence the black-dot experience is the practical tool to use to trigger the overcoming of the preconception, as we'll see in Subsection 3.3.

When left unexplained, the three discordances above may impede students' access to M2 (round Earth). In theories that consider only the model without its DoV, students might be advised to discard M1 ("erase it from memory"), although M1 has been coherent and successful with their experiences thus far (white dot experiences: housebuilding).

But the discordances cited above are a consequence of paying attention only to the model, as if it were all of the knowledge involved. The DoV framework offers an alternative view of knowledge. There is no need to "throw away" M1 (third discordance), and the first two discordances are mitigated if the teacher explicitly teaches the concept of DoV when explaining that M1 "does not work here" (in this context, at this level of analysis, or for this purpose). Moreover, the overgeneralisation process that leads the student to build an ODoV for M1 is more likely if teachers and students only discuss knowledge as models, rather than models associated to DoVs.

Our hypothesis also explains why, even when students understand M2, they may continue to apply M1 (the oscillation mentioned in Subsection 1.4). It is different to remember, understand, explain or even apply a model (which involves only the model itself) than it is to analyse a situation or experience and then select an appropriate model (which involves both the model and its DoV). Students could have learned and remembered a model M2 without having modified the DoV of a model M1. This failure to modify the DoV is more likely if teachers focus primarily on models without explicitly attending to DoVs. Since the DoV is related to the interaction with the environment and is often unconscious, it takes time and repetition to modify the associated model selection process.

In sum, the idea that knowledge is made of coexisting models each with their own DoV explains many of the learning phenomena addressed by the misconceptions and conceptual change literature in science education.

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

3.3. Overcoming the preconception

Our propositions above have important consequences in terms of instructional design. Overcoming ODoV-based preconceptions does not involve throwing away or even modifying the initial model itself (M1), but simply reducing its associated DoV (and accepting a multiplicity of models that are applicable in different situations). What needs to be “abandoned” is only its use *in relation to* the paradoxical experience. According to our theory, the downsizing of the ODoV opens the door for the student to consider a second model with a DoV appropriately covering the black-dot experience.

Reducing the applicability of a model may seem counterintuitive when a key goal of teaching is to enable students to *transfer* what they have learned, i.e. apply a set of principles or model to a *broader range* of situations than originally taught. Transfer, a key pedagogical challenge (Salomon & Perkins, 1989), can also be described as dependent upon awareness of the appropriate DoV associated with a model (i.e. finding new "white dots": situations when the model is appropriate). Transfer, though, emphasises the *expansion* of a model’s domain of validity. Overcoming a preconception involves *reducing* an overgeneralised DoV (i.e. excluding the "black dots": situations for which the model is inappropriate). Therefore, the DoV framework presents a unique extension of research on transfer, not a contradiction. Making explicit the concept of a domain of validity and our hypothesis of a two-component model of knowledge links these two pedagogical challenges (misconceptions and transfer) theoretically. To our knowledge, this linkage has not been made before, though a full investigation of transfer is beyond the scope of this paper.

In conclusion, our DoV framework suggests shifting focus from the model itself to the domain of validity of a given model and directs the attention of the teacher towards reducing overgeneralised DoVs instead of replacing “wrong” or “naïve” models. In

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

Section 5 we build an explicit teaching strategy that attends to *both* components of knowledge. First, we discuss further how the proposed framework aligns with the constructs reviewed earlier.

4. The DoV framework as an integrative step

In this section, we reinterpret the constructs from existing literature described in Section 1 in the new terms of the formalised elements constituting the DoV framework as explained in Section 3. We show the coherence and integrative power of the DoV framework in relation to the extant literature. Obviously, as with any model, the DoV framework does not have an infinite range of application (domain of validity). We note this limitation and call for empirical testing in a range of situations beyond university-level engineering and physics courses.

4.1. Ideas and issues

In Section 2 we highlighted several discrepancies found in the existing literature reviewed in Section 1. Each of these, in the six key constructs, is reconciled by our DoV framework.

One discrepancy is whether prior conceptions must be removed to reach expert conceptions (*misconception*) (Hammer, 1996; Smith et al., 1994) or whether they can be positive and useful on the way to accessing a new model (Brown & Clement, 1987; Clement, 1991, 1993; Clement et al., 1989; Hammer, 2000). Introducing a two-component view of knowledge (model plus domain of validity) allows both perspectives to be valid: the model is useful and needs to be retained, while the domain of validity needs to be altered.

Another discrepancy is between a discontinuous versus continuous view of learning, discussed in Subsection 1.3 and Section 2. According to the DoV framework, the process may be seen as both continuous and discontinuous. Continuity is found (1) insofar as initial models are kept and ideally linked to new models at the end of the process and (2) through recursiveness: when a learning cycle is complete, the association of a new model M2 with another overgeneralised DoV may be the next preconception. This process can be seen as an extension of the relationship between *cognitive obstacles* and the retrospective aspects of learning (Astolfi, 2006; Bachelard, 1938; Fabre, 1995). So, the "naïve/expert" divide is replaced by a potentially infinite sequence of conceptions subject to continual refinement of both models *and* their domains of validity. This gradual process is similar to the *anchoring example* teaching approach (Clement, 1993), the reorganisation of intuitive ideas in the *p-prims* construct (diSessa, 1993; Hammer, 1996; Smith et al., 1994), the excursive journey through liminal states in the *threshold* construct (Cousin, 2006b; Land et al., 2005), the *cognitive conflict* process (Brousseau, 1989a; Piaget, 1967) and the successive (conflicting) assimilations in the *framework theory* approach (Vosniadou, 2012; Vosniadou et al., 2007). This recursive and potentially infinite evolution of students' knowledge explained by the DoV framework echoes the way philosophers of science describe the never-ending progress of scientific knowledge (Kuhn, 1970; Lakatos, 1978).

Discontinuity is found (1) in restricting the DoV of the initial model (hence *abandoning* that model to represent a specific experience) as with the context-sensitivity of *p-prims* (diSessa, 1993; Hammer, 1996; Smith et al., 1994), boundedness of the *threshold concept* (Cousin, 2006a; Cullen, 2010; Land et al., 2005)), but more importantly (2) in accessing a new model (M2) as with *cognitive rupture* (Brousseau, 1989a; Piaget, 1967), *conceptual change* by accommodation (Posner et al., 1982) that allows a new interpretation of the world (first *misconception*'s property (Hammer, 1996; Smith et al., 1994), transformativeness of the *threshold concept*), and (3) making links previously unknown between this new model and the initial one (integrativeness of the *threshold concept*).

In Subsection 3.2, we described three different types of discordances (cognitive, affective and epistemological) that may occur when facing the paradoxical experience and argued that the DoV approach could ease or eliminate those discordances. Defining knowledge incorporating both a model and its domain of validity accommodates the various key ideas contained in existing literature and resolves discrepancies between different constructs. As such, adopting a two-component view of knowledge mitigates all three learner-felt discordances.

4.2. Reinterpreting existing key constructs

The DoV framework uses a small number of concepts: *knowledge*, *model*, *domain of validity* (as a part of an individual's cognitive structure) and *experiences* (including *paradoxical experiences*). To build further definitions, we use the term *conception* as a synonym of *knowledge*. As defined in Subsection 3.1, knowledge consists of an association of a *model* and a *domain of validity*.

We call the *initial conception* the level N knowledge (M1 in Figure 2), and the *target conception* the level N+1 knowledge (M2). The *initial conception* (N) is the prior knowledge of the student. The *target conception (N+1)* is the knowledge the teacher wants the student to learn. The framework we propose is recursive (unfolding over a series of iterative learning cycles), so that there is a succession of learning cycles moving from N to N+1.

In this section, we explicitly reinterpret key constructs from existing literature using the terminology of the DoV framework.

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

Preconception

In Subsection 1.1, we used existing literature to define a preconception as: (1) knowledge which affects how students understand natural phenomena and scientific explanations; (2) stable (strongly held, difficult to change) cognitive structures; (3) constructed by students (via experiences, formal learning, etc.) prior to the considered instruction; (4) forming barriers to new learning.

Building on the DoV framework, we propose two additional defining features of *preconception*: (5) knowledge is the association of a model and a domain of validity; (6) a preconception is knowledge containing an overgeneralised domain of validity that includes experiences that are not properly addressed by the associated model.

Thus, a preconception including properties (5) and (6) could be called a *DoV-based preconception*. We do not claim that all preconceptions are *DoV-based preconceptions*.

As explained in Subsection 3.2, a preconception is stable (item (2)) because it has been useful to understanding the world until encountering the paradoxical experience.

Misconception, alternative conception and anchoring conception

We put the term misconception (as defined in Subsection 1.1) aside because it suggests knowledge may be intrinsically false and should be removed, which is not aligned with our first hypothesis (Subsection 3.1). Alternative conceptions (Clement, 1993; Gilbert & Watts, 1983; Nussbaum & Novick, 1982) and anchoring conceptions (Clement, 1993; Clement et al., 1989; Hammer, 2000; Hestenes, 1987) are initial conceptions in which "valid" knowledge would be included and even used to build target knowledge. This is exactly what our model describes in more detail, suggesting that (nearly) all initial conceptions are alternative conceptions and possibly anchoring conceptions (as defined in Subsection 1.2).

However, embedded in all those constructs is an understanding of "conceptions" as focusing on models only, with insufficient attention to the domains of validity of those models. Our term *DoV-based preconception* makes the source of the problematic knowledge element clear.

P-prims

In p-prims, there are two key ideas: (1) the students' answer is an on-the-spot construction, and (2) lower level (abstract) fundamental primitives are used to build higher level models (diSessa, 1993; Hammer, 1996; Smith et al., 1994).

Both of these elements are compatible with the DoV framework. Though, like alternative conceptions and anchoring conceptions, they also focus primarily on models, rather than being explicit about domains of validity. By reducing models to their primitive parts, p-prims come closer to recognising the problem of how and when different "pieces of knowledge" are invoked in a given situation. That construct also highlights the importance of the situation ("context-sensitivity") (Hammer, 1996), though it does not explicitly explain the association between models and domains of validity.

Troublesome knowledge and threshold concepts

According to the DoV framework, troublesome knowledge could be defined as a target conception (rather than the initial conceptions described by the other constructs) for which assimilation is troublesome for the students. The origin of this troublesome character has been discussed in Subsection 3.2, as occurring when knowledge is seen as focusing only on the model without attending to its domain.

Thus, the DoV framework offers a different explanation for why some target conceptions are “troublesome” for students. Namely, troublesomeness isn’t inherent in the model but in a lack of awareness of the association between a model and its domain of validity.

There is ambiguity in the definition of the threshold concept insofar as some key features clearly refer to a target conception (e.g. the bounded, integrative and troublesome features of the threshold concept), while others refer to the process of shifting from an initial conception to a target conception (e.g. the transformative, irreversible and troublesome features of the threshold concept). The DoV framework, by defining the transition (ODoV downsizing process) between an initial conception (M1) and a target one (M2), offers disambiguation.

Finally, the DoV framework is consistent with the five key characteristics associated with *threshold concepts* (see Subsection 1.4). The property of “boundedness” (Cousin, 2006a; Cullen, 2010; Land et al., 2005) comes closest to capturing the boundedness of a DoV, although the literature on thresholds does not elaborate “boundedness” and does not distinguish between models and DoVs. In our terminology, confronting a paradoxical experience is likely to be troublesome and once a new model is introduced (following the shrinking of the ODoV of the initial model), the result may be *transformative* (and potentially *irreversible*). Likewise, students may experience a *liminal state* when the domain of validity of the initial conception is being challenged and re-sized (during cognitive conflict). However, the DoV framework does not require that all those properties are present, though their presence is not incompatible with our propositions.

Cognitive obstacle and conceptual change

According to the classical frameworks (Astolfi, 2006; Brousseau, 1989b, 1989a; Fabre, 1995), a cognitive obstacle is an initial model present in the student's mind and acting as an obstacle to new knowledge. In the DoV framework, the element preventing access to a new model is not so much the model, but the overgeneralisation of the domain of validity of the initial model.

Referring to Piaget's definition (Subsection 1.5), *cognitive conflict* is the discomfort experienced by a student originating from various discordances as described in Subsection 3.2. In the DoV framework, Piagetian *cognitive conflict* is stimulated by a *paradoxical experience*.

Finally, *conceptual change* is the transition from an initial conception to a target conception involving a *cognitive rupture* process (Piaget, 1967; Posner et al., 1982; Strike & Posner, 1985). It corresponds in the DoV framework to a series of ruptures leading to the target conception: (1) understanding that the initial domain of validity was overgeneralised (for instance by considering differences between “black dot” and “white dot” experiences) and subsequently reducing it, (2) the discovery of the target model and its better fit than the initial model with the new situation, and (3) the discovery of the links between the initial and target models that makes overcoming the preconception acceptable.

In sum, the DoV framework accounts for and resolves discrepancies between a number of existing constructs in the literature. Nevertheless, while it explains some of the divergences observed in previous research, it is not intended to explain *all* these types of learning difficulties. The reviewed constructs are often seen as complementary. For example, the authors of the *knowledge in pieces* perspective did not claim that all knowledge is structured as p-prims, but that this new perspective offered a previously undescribed level of knowledge structure (diSessa, 2014; Hammer, 1996). They suggested that an inclusive view admitting both *conceptual framework* and *knowledge* *in pieces* perspectives is likely necessary to fully explain student knowledge. This complementary approach is consistent with other attempts at syntheses that explain disparate individual observations of difficult-to-change preconceptions (Brown, 2014; Chi, 2013; Hammer, 1996; Hammer, Elby, Scherr, & Redish, 2005; Taber, 2008). Likewise, we offer a new perspective that complements and extends existing major explanations.

5. An effective teaching strategy derived from the DoV framework

Coming back to the DoV framework itself, we now discuss its operational power by illustrating how it underpins a general teaching strategy to overcome preconceptions, that may be used in a various of science education situations.

Since a preconception is hypothesised to be due to an overgeneralisation of a DoV, when teachers face an “error” (and more specifically a recurrent and difficult-to-overcome “error”) from one or several students, the DoV framework approach suggests the following general strategy to facilitate the ODoV preconception overcoming process:

1. Map student’s knowledge and teacher’s (target) knowledge using models and DoVs, as in Figure 2. If the observed situation reveals an oversized DoV by the student(s), proceed with the following steps.
2. Imagine a situation that is located between the DoV and the ODoV of M1 (black-dot experiment): inside student’s ODoV but outside teacher’s DoV. Present this situation to the student.
3. Ask the student to reason about it, guiding him/her if necessary, to the contradiction that using M1 for that situation inevitably provokes. Help the student to concurrently (a) realise that the contradiction comes from the

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

unsuitable application of M1 to that specific situation (hence the need to reduce students' M1 DoV) and (b) imagine a different model (M2) that would be applicable to the situation.

4. Help the student integrate all these elements (M1 with its reduced DoV, M2 with its own DoV, relationships – if any – between M1, M2 and their DoVs) in a new and coherent structure.

The same four-step strategy can then be applied if the student associates an ODoV to the new model M2, or if the teaching sequence or curriculum involves a series of intermediary target knowledge successively building on each other. The DoV framework is therefore a simple and powerful tool able to describe static situations (knowledge's mapping and preconceptions' diagnosis) as well as dynamic situations (teaching strategy and learning process, including the recursive and potentially infinite evolution of students' knowledge).

As an example, let us suppose an 8-year-old European girl asks "why don't Australians fall off the Earth?" The reaction of a teacher would be:

1. To map the situation as:
    - M1 is the model "gravity attracts matter downwards" (initially the only model owned by the student).
    - M2 is the model "gravity attracts matter towards the centre of the Earth" (or an alternative, wider one: "matter attracts matter by gravity and Earth is a lot of matter"), also held by the teacher.
    - Student's DoV for M1 (oversized): M1 is applicable to the situation of Earth (and people on it) in Space, supposing a "downward" direction that would be in the direction of the ground for European people.

- Teacher's DoV: M1 is applicable locally on Earth; M2 is applicable to a wider set of situations (explain the presence of atmosphere, discuss whether people would fall or not "in Space" depending on their latitude on Earth, etc).

2. In this example, the question initially raised by the girl is already a paradoxical experience (Australians obviously do not fall off and thinking that they would is the result of applying M1 outside of a local situation). So, one option would be to simply confirm to the girl that her question is relevant and interesting, and reinforce the troublesomeness of it: "Yes, it's true that the Australians do not fall. It's strange. How it is possible?". Another option would be to question the question itself: "What makes you think they would fall off?" This option has the advantage of triggering metacognition by the student. A third option would be to identify another paradoxical experience in the same area of the DoV: "What is our latitude?", or more simply: "Do you think we are on top of the Earth?". But in any case, what is sent to the student is a question, encouraging her to reason.
3. Mainly by asking questions[6], the teacher encourages the girl to reason herself and to be confident in her reasoning by confirming the relevant elements she provides. For example: "Yes, we are attracted downwards; yes, the Australians do not live at the same position on Earth, and yes they do not fall. (So again,) what makes you think they would fall off?". In this case, this should make the girl express, maybe using a drawing, that she places (unconsciously) the Earth in a vertical referential in Space. Which allows the teacher in turn to ask "then why

[6] We follow here a constructivist approach since the teacher, instead of immediately giving the final explanation, guides the student via questions and reasoning to make him/her infer it him/herself.

do the Moon and other planets not crash into the Earth?", reinforcing the contradiction again. Step by step, she can be guided to express that "vertical direction" is relative to the place on Earth, not to a general direction in Space (asking for example: "when Australians drop an object, where does it fall?"). So, the double conclusion follows: (a) M1 is not applicable to discuss whether people fall or not in Space, but only to a more limited set of situations, and (b) a suitable model for that question is "people are attracted towards the centre of the Earth" (M2).

4. Help the girl express that these conclusions are not contradictory and most of her reasoning was relevant: M1 is applicable locally and is a simplification of M2, which is more suitable at a larger scale. Her only "error" was applying M1 to a non-local situation, where it is not supposed to be applied.

It may be that many science teachers do have that specific conversation with their students. However our point here is to illustrate that what guides the teacher is (a) a goal: making the student downsize the ODoV of M1 (to allow him/her to imagine the possibility of another model M2) and (b) a tool, using a paradoxical experience to push the student to reason in the appropriate direction. This method helps even a young science student learn that knowledge consists of *both* a model (gravity pulls "downward") and its domain of validity (local to one's own spot on Earth).

In this procedure, a key point is to make students become confident in their reasoning, which is a key resource for them. Asking the student questions will also allow the teacher to confirm, disconfirm, or refine the initial mapping as needed. From our experience, the main resource needed by the student is confirmation on specific points by the teacher, so that they have the courage to reason further on alternative models (M2) that may initially seem strange.

While the example above is one of dialogue, there are other ways to guide students through the key steps of the general strategy. For example, a written exercise for an entire class may focus on common errors (from past examinations, for example), and creation of appropriate paradoxical experiences.

This principle of confronting students with a paradox may be used via many techniques, including the predict-observe-explain (POE) strategy (White & Gunstone, 2014), demonstrate-observe-explain (DOE) strategy (Champagne, Klopfer, & Anderson, 2005), elicit-confront-resolve (ECR) strategy (McDermott, 2005), and the elicit-confront-identify-resolve-reinforce (ECIRR) strategy (Wenning, 2009). Although using similar processes, our teaching strategy makes explicit what is being confronted: the failure of a model *in the context of a new experience*. It focuses on identifying the student's assumed domain of validity and its appropriateness, in order to use these conceptual change teaching techniques most effectively.

We tested such a strategy in circuit theory sessions in an engineering course at university level (Sommeillier & Robert, 2016, 2017). After having identified the nine most common preconceptions about electricity among second-year engineering students, we developed and implemented a teaching strategy derived from the DoV framework by modifying the content of two exercise sessions. The reference and modified sessions shared the same intended learning outcome: being able to solve electrical circuits (i.e. finding the voltages across and the currents through every component). The reference exercise sessions consisted mainly in drilling the students in solving circuits from A to Z, through many computations without intuitive, qualitative or interpretative questions, and without any DoV-based teaching strategy. The modified sessions followed a teaching strategy similar to the one described above with various questioning techniques (traps, incorrect demonstrations, qualitative questions, openended problems, etc). The teaching assistants were briefed on the new approach. An experimental pre-test/post-test design – the intervention group following the modified sessions and the control group following the previous versions of the sessions – found that the intervention group of students achieved significantly better results (75% success) on the post-tests in comparison with the control group (50% success). Full details are reported elsewhere (Sommeillier & Robert, 2020).

Our second example, still focused in solving electrical circuits (network analysis) at university, level, uses the DoV framework to analyse the curriculum itself and suggest a revision to its structure and sequence. As reported in (Theunissen, Sommeillier, & Robert, 2020), applying the framework to this problem made us formalise that choosing the appropriate method to solve an electrical circuit may be described by 4 models (representing different circuit solving methods) and their 4 associated DoVs. These last ones may be defined using 3 binary criteria (introducing a distinction between 2^3=8 types of circuits). Figure 4 represents the models, the DoVs and the criteria. To give a couple of examples:

- M3 which is the use of phasors (circuit solving in the frequency domain) is suitable to solve resistive (R) or reactive (C/L), DC or AC circuits in steady state (so without transient, as explained by the fact the switch is outside the DoV associated to M3).
- M4, the use of long-term behaviours of reactive elements, is suitable only to solve reactive DC circuits in steady state.

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

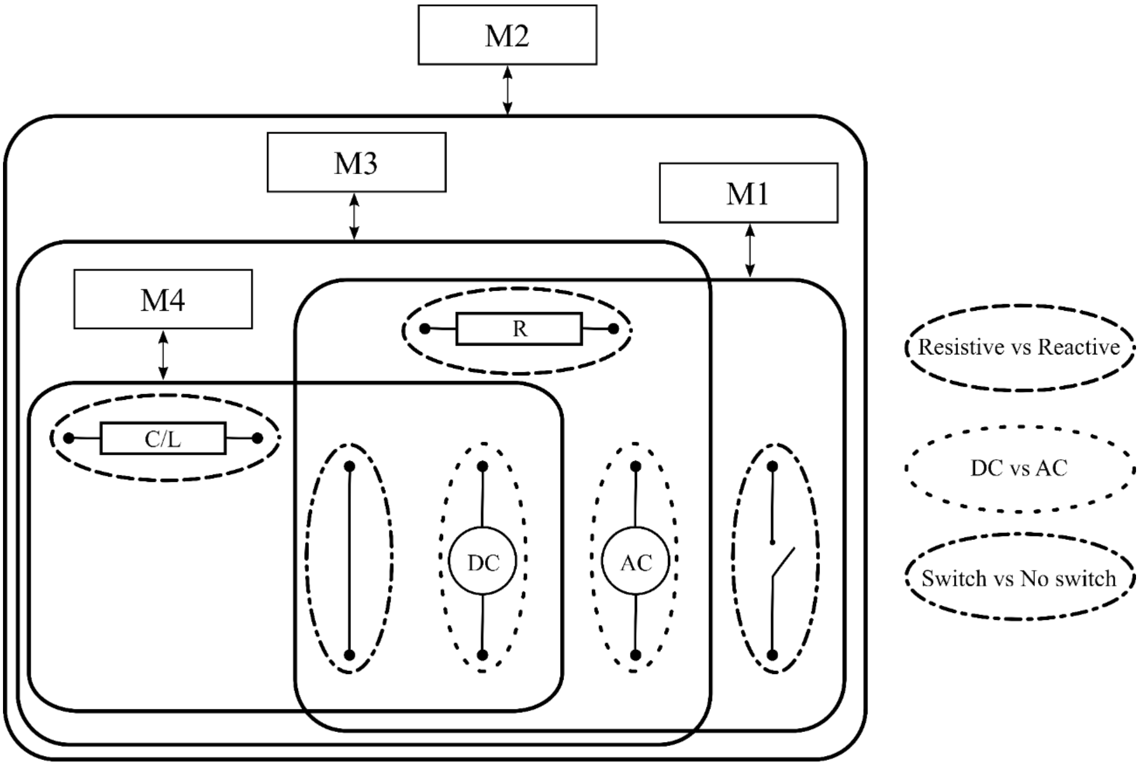

Figure 4. Application of the DoV framework to electrical circuit solving (network analysis)

Using this representation suggested three different (and complementary) ideas to revise our own electricity course and related teaching practices.

The first one is the possibility of mapping in more detail recurring students' errors according to the way they select solving methods (models), and the possibility to help them overcome their underlying learning difficulties – or what we call "methodological preconceptions" using the strategies detailed above.

The second one is to write an online application to investigate the possibility of automating (to some extent) the overcoming of preconceptions for this specific problem (electrical circuit solving). A first small-scale pre-test/post-test design with 37 students showed that after just 15 min of using the application 64% of the participants improved their scores.

Last but not least, this way of modelling the choice of the method when solving electrical circuits made us rethink the teaching sequence of methods, according to the size of their DoVs. The classical way of teaching circuits consists of exploring resistive circuits and reactive circuits (including switches) with continuous sources, then reactive circuits with sinusoidal sources. However, the idea of following an increasing size of the DoVs of the different models suggests teaching reactive circuits with sinusoidal sources before reactive circuits (with switches) with continuous sources. The classical way of teaching implies first expanding and then shrinking the DoV, rather than progressively expanding or shrinking it. We hypothesise that it is the comings and goings in terms of DoV size that create learning obstacles unnecessarily for students, in a subject that is notoriously difficult for them to understand.

While other theories have touched upon domains of validity, the instructional implications have received little attention. For example, Givry and Tiberghien (2012) extensively analysed (via written worksheets and hours of video data collected in the classroom and in the lab) the interaction between two 15-year old students in a physics course related to gases. Having identified three processes of learning: "(1) establishing links between ideas, (2) increasing the domain of applicability of ideas, or (3) decreasing the domain of applicability of ideas" (Givry & Tiberghien, 2012, p. 223), they observed than the third process occurs much less often than the second one. They concluded their paper with implications for teaching strategy: one is about the first process (which is not of interest here), and the second "concerns the process of increasing the domain of applicability […] Consequently, we suggest designing teaching sequences in which the same scientific concepts will be involved systematically by students in several situations. Furthermore, we consider that this learning process should be explicitly assessed by teachers to help students develop a better understanding of these aspects of their learning." (Givry & Tiberghien, 2012, p. 245)

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

Hence while Givry and Tiberghien (2012) explicitly observed and identified downsizing of the "domain of applicability" they do not discuss it in relation to teaching strategies. Furthermore, they suggest the opposite teaching strategy that, arguing that students already often do it spontaneously. In fact, one could argue that students need more help with downsizing domains of validity because they rarely do it on their own. Using very similar elements (models and domains of validity), but linking them explicitly to preconceptions, our framework comes to opposite conclusions. We have built strategies specifically oriented towards Givry and Tiberghien (2012) third process, suggesting its power in overcoming recurrent students' errors.

This example (Givry & Tiberghien, 2012), of reinforcing a generalisation strategy, brings us back to our earlier points in relation to transfer (Subsection 3.3). The authors do not seem to consider that two different situations exist between a model and a new experiment: the "white dot" situation (for which generalisation is the way to go, but does not involve a problematic preconception) and the "black-dot" situation (for which downsizing the ODoV is required).

These various examples illustrate that the DoV framework suggests a general method that can be applied to many situations. It offers practical strategies to help overcome preconceptions in very local situations (discussion with a student, exercise session) as well as more general course design (sequence to teach electrical circuit solving, choice of teaching strategy in relation to expected learning process). In many cases, it suggests new ways of teaching because of its foregrounding of the domain of validity as the key element when trying to address preconceptions.

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

6. Conclusion

By embracing a two-component view of knowledge and explicating the domain of validity of various models, we propose a new theoretical framework in science education useful to both understanding and addressing difficult-to-change prior knowledge. Our model explains the obstacle to learning as an overgeneralised DoV.

The significance of the DoV framework lies not only in its explanatory value, but also in its action-oriented approach. We propose an instructional technique in which students confront a paradoxical situation so that the student realises the limits of the original DoV and subsequently both reduces the domain of validity of the original model and searches for an alternative model. This instructional approach also emphasises the importance of teaching not just models, but their domains of validity. This instructional approach, then, also means being explicit about the two components of knowledge.

We have demonstrated the integrative power of the DoV framework in relation to six scientific constructs related to prior knowledge, firstly by resolving apparent discrepancies between these constructs, and secondly by redefining (or at least linking with our model) known concepts in the literature using a small set of simple and precisely defined terms. Doing so clarifies the relations between initial conception, target conception and the process of going from the former to the latter via cognitive conflict and cognitive rupture.

Although we claim that our framework has high integrative power, it has its own domain of validity like any other model. It does not address all the issues related to prior knowledge and conceptual change. While our experiments in the field of electrical engineering show promising results (Sommeillier & Robert, 2016, 2017, 2020), further research is needed to demonstrate its broad applicability across fields of science and levels of education.

Notes on contributors

Raoul Sommeillier is a Ph.D. candidate in science education specialising in didactics in applied sciences, a teaching assistant in electricity and electronics at the Bio-, Electro- And Mechanical Systems (BEAMS) department, and an engineer in electromechanics. His research focuses on higher education students' preconceptions in scientific fields and the development and testing of teaching strategies to help students overcome these learning obstacles. He holds a double Master of Engineering in mechatronics and constructions from Université libre de Bruxelles (ULB) and Vrije Universiteit Brussel (VUB), an Advanced Master in technological & industrial management from Solvay Business School and an upper secondary teaching certificate in engineering sciences.
https://orcid.org/0000-0002-4903-3386
http://beams.ulb.ac.be/users/raoul-sommeillier
https://be.linkedin.com/in/raoul-sommeillier

Kathleen M. Quinlan is Professor of Higher Education and Director of the Centre for the Study of Higher Education at the University of Kent. Before joining the University of Kent in 2016, she held academic and leadership positions in educational development at the University of Oxford, The Australian National University and Cornell University's College of Veterinary Medicine. She holds a Ph.D. in education from Stanford University and a bachelor's degree in psychology from the University of Maine. Her research focuses on teaching and learning in higher education, with special attention to discipline-specific pedagogical concerns and the development of students' interest in their subjects.
https://orcid.org/0000-0003-3606-4148
https://www.kent.ac.uk/cshe/people/staff/quinlan2.html
https://www.linkedin.com/in/kathleen-m-quinlan-12a0111b/

Frédéric Robert is Dean and Professor in electricity and electronics at the Brussels Faculty of Engineering. He has held various positions within the Université libre de Bruxelles (ULB): Advisor to the Rector for teaching and learning in higher education,

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

Vice-Dean of the École polytechnique de Bruxelles and Head of the Embedded Electronics research unit of the Bio-, Electro- And Mechanical Systems (BEAMS) department. From 2005, he supervised the engineering education department of the École polytechnique de Bruxelles: the Bureau d'Appui Pédagogique en Polytechnique (BAPP). His research interests include science education (project-based learning, conceptual change, cognitive obstacles) and both advanced engineering in electricity and electronics (high frequency transformers, high energy physics instrumentation, industrial electronics). He holds a Ph.D. in Applied Sciences and a Master of Engineering in electronics and telecommunications.

https://orcid.org/0000-0001-6520-5873

http://beams.ulb.ac.be/users/frédéric-robert

https://www.linkedin.com/in/frédéric-robert-3881253/

References

Anderson (Ed.), L. W., Krathwohl (Ed.), D. R., Airasian, P. W., Cruikshank, K. A., Mayer, R. E., Pintrich, P. R., … Wittrock, M. C. (2001). *A taxonomy for learning, teaching, and assessing: a revision of Bloom's taxonomy of educational objectives*. New York: Longman.

Astolfi, J.-P. (2006). *L'erreur, un outil pour enseigner* (7e édition). Paris: ESF éditeur.

Bachelard, G. (1938). *La formation de l'esprit scientifique*. Paris: Vrin.

Baillie, C., & Johnson, A. (2008). A Threshold Model for Attitudes in First Year Engineering Students. In R. Land, J. H. F. Meyer, & J. Smith (Eds.), *Threshold concepts within the disciplines* (pp. 143–154). Rotterdam: Sense Publishers.

Batzli, J. M., Knight, J. K., Hartley, L. M., Maskiewicz, A. C., & Desy, E. A. (2016). Crossing the threshold: Bringing biological variation to the foreground. *CBE Life Sciences Education*, *15*(4), es9. https://doi.org/10.1187/cbe.15-10-0221

Brousseau, G. (1983). Les obstacles épistémologiques et les problèmes en mathématiques. *Recherches En Didactique Des Mathématiques Grenoble*, *4*(2).

Brousseau, G. (1989a). Les obstacles épistémologiques et la didactique des mathématiques. *Construction Des Savoirs , Obstacles et Conflits*, pp. 41–63.

Brousseau, G. (1989b). *Obstacles épistémologiques, conflicts socio-cognitifs et ingéniérie didactique*. 277–285. Université de Québec, Montréal, Canada: N. Bednarz, C. Garnier (Eds.).

Brown, D. E. (2014). Students' Conceptions as Dynamically Emergent Structures. *Science and Education*, *23*(7), 1463–1483. https://doi.org/10.1007/s11191-013-9655-9

Brown, D. E., & Clement, J. (1987). Overcoming Misconceptions in Mechanics: A Comparison of Two Example-Based Teaching Strategies. *Paper Presented at the Annual Meeting of the American Educational Research Association*. Washington

DC.

Caravita, S., & Halldén, O. (1994). Re-framing the problem of conceptual change. *Learning and Instruction*, *4*(1), 89–111. https://doi.org/10.1016/0959-4752(94)90020-5

Carey, S. (1986). Cognitive Science and Science Education. *American Psychologist*, *41*(10), 1123–1130. https://doi.org/https://doi.org/10.1037/0003-066X.41.10.1123

Champagne, A. B., Klopfer, L. E., & Anderson, J. H. (2005). Factors influencing the learning of classical mechanics. *American Journal of Physics*, *48*(12), 1074–1079. https://doi.org/10.1119/1.12290

Chi, M. T. H. (2008). Three Types of Conceptual Change: Belief Revision, Mental Model Transformation, and Categorical Shift. In S. Vosniadou (Ed.), *International Handbook of Research on Conceptual Change* (pp. 61–82). Routledge.

Chi, M. T. H. (2013). Two Kinds and Four Sub-Types of Misconceived Knowledge, Ways to Change it, and the Learning Outcomes. In S. Vosniadou (Ed.), *International Handbook of Research on Conceptual Change* (2nd ed., pp. 49–70). https://doi.org/10.4324/9780203154472.ch3

Clement, J. (1991). Non-formal reasoning in experts and science students : The use of analogies, extreme cases, and physical intuition. In J. Voss, D. Perkins, & J. Segal (Eds.), *Informal Reasoning and Education* (pp. 345–362). Hillsdale NJ: Lawrence Erlbaum Associates.

Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. *Journal of Research in Science Teaching*, *30*(10), 1241–1257. https://doi.org/10.1002/tea.3660301007

Clement, J., Brown, D. E., & Zietsman, A. (1989). Not all preconceptions are misconceptions: Finding 'anchoring conceptions' for grounding instruction on students' intuitions. *International Journal of Science Education*, *11*(5), 554–565. https://doi.org/10.1080/0950069890110507

Closset, J.-L. (1983). Le Raisonnement Séquentiel en Électrocinétique. *Bulletin de l'Union Des Physiciens*, *657*, 81–102.

Closset, J.-L. (1992). Raisonnements en électricité et en hydrodynamique. *Aster*, *14*(4), 143–155.

Cokelez, A., & Dumon, A. (2005). Atom and molecule: Upper secondary school French students' representations in long-term memory. *Chemistry Education Research and Practice*, *6*(3), 119–135. https://doi.org/10.1039/B4RP90005G

Cousin, G. (2006a). An introduction to threshold concepts. *Planet*, (17), 4–5. https://doi.org/10.11120/plan.2006.00170004

Cousin, G. (2006b). Threshold concepts, troublesome knowledge and emotional capital. In *Overcoming Barriers to Student Understanding: Threshold Concepts and Troublesome Knowledge* (pp. 134–147).

Cullen, D. (2010). Threshold Concepts and Troublesome Knowledge in Curriculum Design. In *Principles in Patterns (PiP) Project Report*.

Demirci, N., & Çirkinoglu, A. (2004). Determining Students' Preconceptions/Misconceptions in Electricity and Magnetism. *Journal of Turkish Science Education*, *1*(2), 51–54.

diSessa, A. A. (1986). Knowledge in pieces. In G. Forman & P. Pufal (Eds.), *Constructivism in the computer age*. https://doi.org/10.1159/000342945

diSessa, A. A. (1993). Toward an Epistemology of Physics. *Cognition and Instruction*, *10*(2–3), 105–225. https://doi.org/10.1080/07370008.1985.9649008

diSessa, A. A. (2014). A History of Conceptual Change Research: Threads and Fault Lines. In *The Cambridge Handbook of the Learning Sciences, Second Edition* (K. Sawyer, pp. 88–108). https://doi.org/10.1017/CBO9781139519526.007

Drechsler, M., & Schmidt, H.-J. (2005). Textbooks' and teachers' understanding of acid-base models used in chemistry teaching. *Chemistry Education Research and Practice*, *6*(1), 19–35. https://doi.org/10.1039/B4RP90002B

Driver, R., & Easley, J. (1978). Pupils and paradigms: A review of literature related to concept development in adolescent science students. *Studies in Science Education*, *5*(1), 61–84. https://doi.org/10.1080/03057267808559857

Duit, R., Treagust, D. F., & Widodo, A. (2013). Teaching Science for Conceptual Change. In S. Vosniadou (Ed.), *International Handbook of Research on Conceptual Change* (pp. 485–503). https://doi.org/10.4324/9780203154472.ch25

Duval, R. (1993). Registres de représentation sémiotique et fonctionnement cognitif de la pensée. *Annales de Didactique et de Sciences Cognitives*, Vol. 5, pp. 37–65. Estrasburgo.

Fabre, M. (1995). *Bachelard éducateur*. Paris: Presses universitaires de France (PUF).

Fetherstonhaugh, T., & Treagust, D. F. (1992). Students' understanding of light and its properties: Teaching to engender conceptual change. *Science Education*, *76*(6), 653–672. https://doi.org/10.1002/sce.3730760606

Fransella, F. (2003). *International Handbook of Personal Construct Psychology* (F. Fransella, Ed.). UK: Wiley. https://doi.org/10.1002/0470013370

Gilbert, J. K., Osborne, R. J., & Fensham, P. J. (1982). Children's science and its consequences for teaching. *Science Education*, *66*(4), 623–633. https://doi.org/10.1002/sce.3730660412

Gilbert, J. K., & Watts, D. M. (1983). Concepts, misconceptions and alternative conceptions: Changing perspectives in science education. *Studies in Science Education*, *10*(1), 61–98. https://doi.org/10.1080/03057268308559905

Givry, D., & Tiberghien, A. (2012). Studying Students' Learning Processes Used during Physics Teaching Sequence about Gas with Networks of Ideas and Their Domain of Applicability. *International Journal of Science Education*, *34*(2), 223–249. https://doi.org/10.1080/09500693.2011.566289

Halloun, I. A. (2006). *Modeling Theory in Science Education*. Dordrecht, The Netherlands: Kluwer Academic. https://doi.org/10.1007/1-4020-2140-2

Halloun, I. A. (2011). From Modeling Schemata to the Profiling Schema: Modeling Across the Curricula for Profile Shaping Education. In *Models and Modeling* (pp. 77–96). https://doi.org/10.1007/978-94-007-0449-7_4

Hammer, D. (1996, January). Misconceptions or P-Prims: How May Alternative Perspectives of Cognitive Structure Influence Instructional Perceptions and Intentions? *Journal of the Learning Sciences*, Vol. 5, pp. 97–127. https://doi.org/10.1207/s15327809jls0502_1

Hammer, D. (2000). Student resources for learning introductory physics. *American Journal of Physics*, *68*(S1), S52–S59. https://doi.org/10.1119/1.19520

Hammer, D., Elby, A., Scherr, R. E., & Redish, E. F. (2005). Resources, framing, and transfer. In *Transfer of learning from a modern multidisciplinary perspective* (pp. 89–120). https://doi.org/10.1002/car.1158

Hamza, K. M., & Wickman, P. O. (2008). Describing and analyzing learning in action: An empirical study of the importance of misconceptions in learning science. *Science Education*, *92*(1), 141–164. https://doi.org/10.1002/sce.20233

Helm, H. (1980). Misconceptions in physics amongst South African students. *Physics Education*, *15*(2), 92–105. https://doi.org/10.1088/0031-9120/15/2/308

Hestenes, D. (1987). Toward a modeling theory of physics instruction. *American Journal of Physics*, *55*(5), 440–454. https://doi.org/10.1119/1.15129

Justi, R., & Gilbert, J. (2000). History and philosophy of science through models: Some challenges in the case of 'the atom'. *International Journal of Science Education*, *22*(9), 993–1009. https://doi.org/10.1080/095006900416875

Kelly, G. A. (2005). A Brief Introduction to Personal Construct Theory. In *International Handbook of Personal Construct Psychology* (pp. 3–20). https://doi.org/10.1002/0470013370.ch1

Krathwohl, D. R. (2002). A Revision of Bloom's Taxonomy: An Overview. *Theory into Practice*, *41*(4), 212–218.

Kuhn, T. S. (1970). *The structure of scientific revolutions*. Fourth edition, 50th anniversary. University of Chicago press.

Lakatos, I. (1978). Falsification and the Methodology of Scientific Research Communities. In *The Methodology of Scientific Research Programmes: Philosophical Papers* (Vol. 1, pp. 8–101). Springer.

Land, R., Cousin, G., Meyer, J. H. F., & Davies, P. (2005). Threshold concepts and troublesome knowledge: Implications for course design and evaluation. *Improving Student Learning Diversity and Inclusivity*, *49*(3), 53–64.

Land, R., & Meyer, J. H. F. (2006). *Overcoming barriers to student understanding: Threshold concepts and troublesome knowledge*. https://doi.org/10.4324/9780203966273

Martinand, J.-L. (1995). La référence et l'obstacle. *Perspectives Documentaires En Éducation*, *34*, 7–22.

McDermott, L. C. (2005). Millikan Lecture 1990: What we teach and what is learned: Closing the gap. *American Journal of Physics*, *59*(4), 301–315. https://doi.org/10.1119/1.16539

Meyer, J. H. F., & Land, R. (2003). Threshold concepts and troublesome knowledge: Linkages to ways of thinking and practising within the disciplines. *Improving Student Learning – Ten Years On.*, *4*(1), 1–16.

Meyer, J. H. F., Land, R., & Baillie, C. (2010). *Threshold concepts and transformational learning*. Boston: Sense Publishers.

Michelet, S., Adam, J.-M., & Luengo, V. (2007). Adaptive learning scenarios for detection of misconceptions about electricity and remediation. *International*

Journal of Emerging Technologies in Learning, *2*(1), 1–5.

National Research Council. (1999). *How people learn: Bridging research and practice*. https://doi.org/10.17226/9457

National Research Council. (2012a). A framework for K-12 science education: Practices, crosscutting concepts, and core ideas. In *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (Vol. 1). https://doi.org/10.17226/13165

National Research Council. (2012b). *Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering*. https://doi.org/10.17226/13362

Novak, J. D. (1977). *A Theory of Education*. London : Cornell University.

Nussbaum, J., & Novick, S. (1982). Alternative frameworks, conceptual conflict and accommodation: Toward a principled teaching strategy. *Instructional Science*, *11*(3), 183–200. https://doi.org/10.1007/BF00414279

Özmen, H. (2004). Some Student Misconceptions in Chemistry: A Literature Review of Chemical Bonding. *Journal of Science Education and Technology*, *13*(2), 147–159. https://doi.org/10.1023/B:JOST.0000031255.92943.6d

Palmer, D. (1997). The effect of context on students' reasoning about forces. *International Journal of Science Education*, *19*(6), 681–696. https://doi.org/10.1080/0950069970190605

Perkins, D. (1999). The Many Faces of Constructivism. *Educational Leadership*, *57*(3), 6–11. https://doi.org/10.1111/j.1467-8535.2009.00994_9.x

Perkins, D. (2006). Constructivism and Troublesome Knowledge. In *Overcoming Barriers to Student Understanding: Threshold Concepts and Troublesome Knowledge* (pp. 33–47). https://doi.org/10.4324/9780203966273

Peşman, H., & Eryilmaz, A. (2010). Development of a three-tier test to assess misconceptions about simple electric circuits. *Journal of Educational Research*, *103*(3), 208–222. https://doi.org/10.1080/00220670903383002

Piaget, J. (1967). Logique et connaissance scientifique. In *Encyclopédie de la Pléiade*. Paris: Gallimard.

Pintrich, P. R., Marx, R. W., & Boyle, R. A. (1993). Beyond Cold Conceptual Change: The Role of Motivational Beliefs and Classroom Contextual Factors in the Process of Conceptual Change. *Review of Educational Research*, *63*(2), 167–199. https://doi.org/10.3102/00346543063002167

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, *66*(2), 211–227. https://doi.org/10.1002/sce.3730660207

Quinlan, K. M., Edwards, D. J., Lubansky, A., Baillie, C., Trevitt, C., Stamboulis, A., & Fill, J. (2012). Exploring engineering thresholds at level 4 : what happens in the Oxford tutorial ? In *Enhancing engineering higher education: Outputs of the national HE STEM programme* (M. Harriso, pp. 89–94). London, UK: Royal Academy of Engineering.

Quinlan, K. M., Male, S. C., Baillie, C. A., & Stamboulis, A. (2013). Methodological challenges in researching threshold concepts: A comparative analysis of three projects. *Higher Education*, *66*(5), 585–601. https://doi.org/10.1007/s10734-013-9623-y

Rittle-Johnson, B., Star, J. R., & Durkin, K. (2009). The importance of prior knowledge when comparing examples: Influences on conceptual and procedural knowledge of equation solving. *Journal of Educational Psychology*, *101*(4), 836–852. https://doi.org/10.1037/a001602

Rozier, S. (1988). *Le raisonnement linéaire causal en thermodynamique classique élémentaire.* Université Paris VII.

Sadler, P., Schneps, M. H., & Woll, S. (1989). A private universe : misconceptions that block learning. Santa Monica: Pyramid Film and Video, produced by Harvard University and the Smithsonian Institution.

Salomon, G., & Perkins, D. N. (1989). Rocky Roads to Transfer: Rethinking Mechanisms of a Neglected Phenomenon. *Educational Psychologist*, *24*(2), 113–142. https://doi.org/10.1207/s15326985ep2402_1

Schwartzman, L. (2010). Transcending disciplinary boundaries: A proposed theoretical foundation for threshold concepts. In Meyer, Jan H. F., Land, Ray, & C. Baillie (Eds.), *Threshold concepts and transformational Learning* (pp. 21–44). https://doi.org/https://doi.org/10.1163/9789460912078_003

Smith, J. P., diSessa, A. A., & Roschelle, J. (1994). Misconceptions Reconceived: A Constructivist Analysis of Knowledge in Transition. *Journal of the Learning Sciences*, *3*(2), 115–163. https://doi.org/10.1207/s15327809jls0302_1

Solomon, J. (1983). Learning about energy: How pupils think in two domains. *European Journal of Science Education*, *5*(1), 49–59. https://doi.org/10.1080/0140528830050105

Sommeillier, R., & Robert, F. (2016). Les préconceptions en théorie des circuits électriques au niveau universitaire : développement d’une stratégie de dépassement. In *9ème Rencontre de l’ARDiST*. Université d’Artois, Lens, France.

Sommeillier, R., & Robert, F. (2017). *Misconceptions in Electricity at University Level: Development of an Overcoming Teaching Strategy*. Dublin City University, Dublin, Ireland.

Sommeillier, R., & Robert, F. (2020). *[under review] Understanding Electrical Circuit Theory at University Level: Development of an Efficient Preconception-centered Teaching Strategy*.

Strike, K., & Posner, G. (1985). A Conceptual Change View of Learning and Understanding. *Cognitive Structure and Conceptual Change*, *211*, 1–20.

Taber, K. S. (2001). The Mismatch between Assumed Prior Knowledge and the Learner’s Conceptions: A typology of learning impediments. *Educational Studies*, *27*(2), 159–171. https://doi.org/10.1080/03055690120050392

Taber, K. S. (2005). Learning quanta: Barriers to stimulating transitions in student understanding of orbital ideas. *Science Education*, Vol. 89, pp. 94–116. https://doi.org/10.1002/sce.20038

Taber, K. S. (2008). Conceptual resources for learning science: Issues of transience and grain-size in cognition and cognitive structure. *International Journal of Science Education*, *30*(8), 1027–1053. https://doi.org/10.1080/09500690701485082

The Version of Record of this manuscript has been published in STUDIES IN SCIENCE EDUCATION on 5 Oct 2020 available online: http://www.tandfonline.com/doi/full/10.1080/03057267.2020.1824472

Theunissen, R., Sommeillier, R., & Robert, F. (2020). Methodological preconceptions and DoV framework : Analysis of students' errors in electrical circuit solving. *11e Rencontres Scientifiques de l'ARDiST*. Brussels.

Tyson, L. M., Venville, G. J., Harrison, A. G., & Treagust, D. F. (1997). A multidimensional framework for interpreting conceptual change events in the classroom. *Science Education*, *81*(4), 387–404.

Vergnaud, G. (1994). Le rôle de l'enseignant à la lumière des concepts de schème et de champ conceptuel. *Vingt Ans de Didactique Des Mathématiques En France, Grenoble, La Pensée Sauvage*, 177–191.

Vergnaud, G. (2009). The theory of conceptual fields. *Human Development*, *52*(2), 83–94. https://doi.org/10.1159/000202727

Viennot, L. (1979). Spontaneous reasoning in elementary dynamics. *European Journal of Science Education*, *1*(2), 205–221. https://doi.org/10.1080/0140528790010209

Viennot, L. (1985). Analyzing students' reasoning: Tendencies in interpretation. *American Journal of Physics*, *53*(5), 432–436. https://doi.org/10.1119/1.14194

Vosniadou, S. (2006). The conceptual change approach in the learning and teaching mathematics: An introduction. *Proceedings, 30th Conference of the International Group for the Psychology of Mathematics Education*, *1*, 155–159.

Vosniadou, S. (2012). Reframing the Classical Approach to Conceptual Change: Preconceptions, Misconceptions and Synthetic Models. In *Second International Handbook of Science Education* (pp. 119–130). https://doi.org/10.1007/978-1-4020-9041-7_10

Vosniadou, S., Baltas, A., & Vamvakoussi, X. (2007). *Re-framing the conceptual change approach in learning and instruction*.

Vosniadou, S., Vamvakoussi, X., & Skopeliti, I. (2008). The framework theory approach to the problem of conceptual change. In S. Vosniadou (Ed.), *International Handbook of Research on Conceptual Change* (pp. 3–34).

Wenning, C. J. (2009). Dealing more effectively with alternative conceptions in science. *Journal of Physics Teacher Education Online*, *5*(1), 11–19.

White, R., & Gunstone, R. (2014). *Probing Understanding*. London and New York: The Falmer Press. https://doi.org/10.4324/9780203761342

Zembylas, M. (2005, January). Three perspectives on linking the cognitive and the emotional in science learning: Conceptual change, socio-constructivism and poststructuralism. *Studies in Science Education*, Vol. 41, pp. 91–115. https://doi.org/10.1080/03057260508560215