Overgeneralized domains of validity: a new theory of preconceptions in science

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Abstract

This paper pulls together disparate pockets of research concerned with common, difficult-to-change conceptions students have about particular scientific topics. We clarify similarities and differences across these bodies of research, highlighting unique contributions of different research traditions. Seeking resolution across these constructs, we propose that knowledge consists of *two* connected elements: a *model* and a *domain of validity* (or *DoV*). Adding the notion of the "domain of validity" for given models - and focusing on problems of overgeneralization of domains of validity - offers a new way forward. We explore the pedagogical implications related to these scientific learning difficulties and conclude by proposing particular teaching strategies based on this new theory, emphasizing the domains of validity of particular scientific models.

Keywords:

Science education, model-based learning, misconception, threshold concept, conceptual change

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Since the early 20th century, science education research has emphasized the importance of understanding students' prior knowledge (National Research Council, 1999). Researchers from various backgrounds, periods and nationalities have studied how difficult-to-change prior knowledge impacts the way students learn, yielding a variety of terminology and concepts that are similar, though with subtle distinctions.

We clarify existing constructs before proposing an integrative new theory. First, we briefly summarize seminal ideas that address similar topics, aim for 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 theory that integrates those key constructs. This theory, based on the notion of "domain of validity" (or DoV) of knowledge, allows us to propose associated teaching strategies.

Third, we reinterpret the constructs from existing literature in the new terms of our overgeneralized DoV theory. This last step shows the coherence and limitations of the proposed theory in relation to the extant literature.

1. Literature Review

Research on "prior knowledge" is organized 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 grounds and points of divergence. For each construct, we succinctly summarize its key features, the contributions it makes beyond previous literature and major criticisms it has faced.

1.1. Misconceptions and Preconceptions

Since the 1960's, the literature refers to students' conceptions under several names, including: *misconceptions* (Helm, 1980), *preconceptions* (Ausubel 1968, Novak, 1977), *alternative conceptions* (Driver & Easley, 1978), *children's science* (Gilbert, Osborne, & Fensham, 1982), and *synthetic models* (Vosniadou, 2006). Some authors employ alternative terms (e.g. *intuitive conceptions*, *naïve beliefs*, *pre-instructional conceptions, spontaneous knowledge, folk knowledge, personal models of reality*) to mean the same idea. 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).

Other researchers do not characterize the relationship between preconceptions or misconceptions and scientifically accepted ideas in terms of conflict (Hammer, 1996; Hamza & Wickman, 2008; National Research Council, 2012; Smith, diSessa, & Roschelle, 1994). For Driver & Easley (1978), the main property of a *preconception* is that it is naïve, immature, or under-developed compared to a scientific concept. An important review of this literature (National Research Council, 2012) uses the term *misconceptions* to mean understandings or explanations that differ from what is known to be scientifically correct but recognize that some researchers refer to these explanations as *alternate conceptions*, *prior understandings*, or *preconceptions*, and that the different terms can reflect different perspectives.

Other authors emphasize its temporal aspect. 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 (Council & others, 2012; Hamza & Wickman, 2008). 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) are stable (strongly held, difficult to change) cognitive structures, (3) differ from expert conceptions, and (4) must be eliminated or dismantled for a student to progress.

In the following sections, this definition will be challenged by other constructs. However, the third and fourth properties– an intrinsic incorrectness of the prior knowledge and consequent need for removal – have already been questioned (Chi, 2008, 2013; Clement et al., 1989; Michelet, Adam, & Luengo, 2007).

Thus, we will use the term *preconception* to depict a more general and neutral concept than *misconception*: knowledge that has the two first properties but, is mainly defined by its presence before formal instruction and by its role as an obstacle to further learning. 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.

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 emphasize building on existing knowledge, which is seen as the product of intentional, active, and ongoing construction by an individual. 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. In sum, "prior knowledge can either interfere with or facilitate new learning" (National Research Council, 1999).

Although this debate has more or less ended, it 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)

This new perspective on the nature of prior knowledge meant that learning was no longer seen as simply dismantling misconceptions. For example, “By changing an alternative conception […] here I mean overcoming the dominance of an alternative conception in inappropriate situations in some way; thus it 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) 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, there may be other preconceptions which 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).

A problem situation is an *anchoring example* for a given student if he or she makes a correct response to the problem and indicates substantial confidence in the answer (i.e. the preconception is strongly held). Based on their experiments, Clement et al. (1989) observed that students’ correct answers to a particular example can trigger an *anchoring conception* that is an extendable 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)

Rooted in constructivism (and more specifically the production of ideas by the students), DiSessa and his colleagues (diSessa, 1986, 1993; Smith et al., 1994) proposed the concept of *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, 2006; Hammer, 1996; Taber, 2008); (2) emphasize 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. He challenged the *conceptual framework* perspective by arguing 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 without having thought about it consciously before. He called these abstract fragmentary knowledge structures that students use to make sense of the world *phenomenological primitives* or *p-prims* (diSessa, 1986, 1993; Hammer, 1996; Smith III, Disessa, & Roschelle, 1994). Thus, DiSessa questioned the first and second properties of *misconceptions/preconceptions* in the definition above (Subsection 1.1).

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 III et al., 1994). As constructivists, Smith et al. (1994) and DiSessa (1986, 1993) argued, like proponents of the alternative frameworks, that the *misconception* perspective offers no account of productive ideas that might serve as resources for learning. By studying expert 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 reorganizing intuitive ideas into better knowledge (diSessa, 1993; Hammer, 1996; Smith III et al., 1994).

1.4. Threshold concept

More recently, Meyer and Land coined the term *threshold concept*. Their thinking was influenced by the works of David Perkins on *troublesome knowledge* (Meyer & Land, 2003, 2006b; Meyer, Land, & Baillie, 2010; 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, 2006; Land, Cousin, Meyer, & Davies, 2005; Meyer & Land, 2006b), though these have not been well-debated or detailed in the literature (Quinlan et al., 2013). We focus here on transformative, 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, or part thereof. These authors add assumptions about the transformative nature of certain key concepts. *Misconceptions*, *alternative conceptions* and *p-prims* may be difficult-to-alter and common, however no claims are made about the importance of those prior conceptions or the centrality of them to progressing in the discipline. By emphasizing the transformative nature of thresholds (captured by their very name), Meyer and Land are signaling the need for special curricular significance.

A threshold concept is also *integrative* insofar as it exposes the previously hidden interrelatedness and connections with other hidden concepts or parts of the discipline. Thus, their integrative nature is another contribution that is also notable and not claimed by other traditions reviewed earlier. Incidentally, this property of “integrativeness” is now emphasized more in recent research about *conceptual change*, notably in the *framework theory approach* developed by Vosniadou, Vamvakoussi, & Skopeliti (2008) (see Subsection 1.5).

A threshold is possibly often (though not necessarily 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 potentially (and possibly inherently) *troublesome*, as it is likely to involve forms of “troublesome knowledge” in the sense of David Perkins. (Meyer & Land, 2003)

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

One difference to previous constructs is that the *threshold* 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 clear distinction. 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, 2006). Nevertheless, Land et al. (2005) also discuss the learning process and implications for teaching. They argue that teachers must be aware that their students can tolerate learner confusion and that, as teachers, they need to support students through liminal states. The learning process is recursive and excursive: there is no simplistic, linear, learning outcomes approach from easy to difficult. The mastery of a threshold often involves many "takes" and looping back on the material.

1.5. Cognitive obstacles

The French educational literature[1] 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 the works of Piaget 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).

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[1] Thus, this part will use terms translated directly (literally) from French terminologies.

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 behaviorist 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, p. 171, translated from French)

From these fundamentals, some authors attempted to define *obstacle*. For instance, Fabre (1995) and Astolfi (1997) elaborated six key features: inwardness, ease, positivity, ambiguity, polymorphy and recursiveness (translated from French[2]). While the three first features are a part of the previous constructs in this paper, the last three bring new contributions.

Ambiguity of obstacles is due to their double status. According to Brousseau (1989a, 1989b), an obstacle is knowledge that, in a certain context, provides suitable solutions to the encountered problems, but that, outside of this context, leads to errors. Thus, *ambiguity* explains why particular knowledge, both functional and blocking, may resist instruction and continues to be used even if the learner is aware of this ambiguity.

Polymorphy expresses the fact that an obstacle cannot be perfectly delimited because its anchors are often multiple. Even if students' representations are local (context or content specific) and seemingly independent, they may share an explanation system rooted in a coherent and deep network of ideas. Thus, polymorphy resembles the integrative property of the *threshold*

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[2] In French : intériorité, facilité, positivité, ambiguïté, polymorphie and récursivité.

concept. Moreover, polymorphy means that the obstacles, in addition to their inherently cognitive features, are in relationship with multiple other dimensions: affective, emotive, etc., a property that has been largely overlooked in the more recent Anglophone literature.

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 metacognitive and retrospective aspects of learning.

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 (Viennot, 1979, 1985), *sequential reasoning* in electrocinetics (Closset, 1983), and *causal linear reasoning* in thermodynamics (Rozier, 1988), as well as the theory of *conceptual fields* of Vergnaud (1994, 2009), the notion of *goal-obstacle* of Martinand (1995) or the works of Vygotski (1997) contributed significantly to the development of this field.

Early French 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 a situation 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 situation. 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*: facing the 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 obstacles the status of knowledge. For Bachelard, some knowledge is essential to learning: the students have to learn (temporary) "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 essential supports to reach 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 constitute intellectual tools that they will retain as long as they see them as offering a higher explanatory value. This can be linked to the *concept exchange model* introduced by Hewson (1981).

1.6. Theory of conceptual change

The first three constructs in this section mainly focused on the nature of the student's knowledge. With the *threshold concept* and the *cognitive obstacle* perspectives, the focus shifted to the *process* by which learners evolve from one set of concepts to another. This process was formalized 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 established a parallel respectively between assimilation and accommodation processes and the “normal science” and “scientific revolution” phases developed by well-known philosophers of science (Kuhn, 1962; Lakatos, 1976). Posner and colleagues (1982) focused their research on *accommodation*.

Posner’s theory of accommodation (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 (1982) 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 and affective dimensions (Caravita & Halldén, 1994) and ignored students’ productive ideas (Smith III et al., 1994).

Taking these criticisms into account, Vosniadou and colleagues (Vosniadou, 2006; Vosniadou et al., 2007) have developed a re-framed conceptual change approach to learning: the *framework theory approach.* This theory is constructivist and sees misconceptions as part of a knowledge system consisting of many different elements organized in complex ways built through successive 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. Emerging ideas and issues

Thus far, we have highlighted links and differences between some of the numerous concepts in science education that explain students' difficult-to-change conceptions. These bodies of research seem to be "circling around" a common pattern, without *explaining* it precisely. Many characteristics appear in more than one construct, either as similarities or as apparently unresolved oppositions. For example, we note the following themes:

The *misconception* construct, and the *theory of conceptual change*, sees "non scientific" prior conceptions as intrinsically incorrect knowledge that must be removed to reach expert conceptions. In contrast, prior knowledge may be positive and useful on the way to accessing a new model in constructs such as *alternative* and *anchoring conceptions*, *p-prims, cognitive obstacles* and the *framework theory* approach to conceptual change.

The conceptual transformation process is seen as having a strong discontinuous character (sometimes seen as irreversible) in the *misconception, threshold concept* and *theory of conceptual change* constructs. However, a more continuous process is envisioned in the *anchoring conception*, *p-prim,* and *framework theory* constructs. The "liminal state" tackled by the threshold concepts construct clearly echoes the "cognitive conflict" studied in the *cognitive obstacle* construct. The troublesome aspect of these situations is also clearly mentioned by these two constructs.

In addition, the nature and status of knowledge seems to differ or converge in the studied constructs. For some constructs, the newly accessed "expert" knowledge is a final (absolute) destination for the learning journey. For others, it is still considered "naïve" compared to further knowledge. The relative and temporary nature of knowledge has already been highlighted by Balacheff (1995) in his comparison between *misconception* and *cognitive obstacle* constructs. As knowledge is temporary and relative, the “recursiveness” of the whole learning process is pointed out. This recursive aspect does not seem to be addressed very explicitly by any of the cited constructs but is mentioned – with slight nuances of meaning – in *threshold concept* and *cognitive obstacle* constructs.

In addition to the divergence in terminology (particularly discussed in Subsection 1.1), we note that definitions are not always present or clear for some of the concepts from the initial constructs. As an example, some properties of the threshold concept refer to a transformation of knowledge while others refer to knowledge itself (see Subsection 4.2). Moreover, depending on the particular construct and its research goals, the underlying focus is sometimes on the learning difficulties or sometimes on the target knowledge or sometimes on the learning process.

Concerning instructional implications, the teaching strategies often remain general, with few explicit procedures to follow when prior knowledge reveals itself to be an obstacle to learning. At one level, all these perspectives have similar instructional implications: they see students’ incorrect statements as reflecting (shared) cognitive structures rather than as individual, nonsensical mistakes. Thus, they suggest it is important for an instructor to explore the students' misunderstandings, uncertainties and prior knowledge and to look for the sense behind students’ incorrect statements. There is less consensus on teachers’ actions after this “diagnostic” phase. The constructs for which students’ conceptions are seen as inherently inconsistent with expert knowledge suggest eliminating, dismantling or replacing prior knowledge, whereas the others suggest exploiting these resources by re-organizing students’ understanding. Exploiting these resources can take different shapes, though. On the one hand, the teacher could choose to support and build on them as a creative and productive act of conceiving and then use these acts of reasoning as steps toward more expert-like understanding. On the other hand, the teacher should create a set of conditions conducive to support students through cognitive conflicts (or liminal states), by making a new conception more intelligible and plausible, by representing content in multiple modes, by using different teaching techniques (e.g. using metaphors, models and analogies, changes of implicit models and languages, socio-cognitive conflicts) or sometimes by acting as an adversary confronting the students when they attempt problematic assimilations.

Finally, many constructs seem to "circle around" without clearly theorizing the notion of the "context of application" of students' conceptions. It is mentioned in *anchoring conceptions*, *p-prims* and *cognitive obstacle* constructs. We also perceive a link between this idea and the "boundedness" feature of the *threshold concept* construct, by bringing it from the discipline level to the knowledge level. We propose that each conception must be studied concurrently with its associated context of application – or its "domain of validity". This proposition offers a new (unifying) perspective capable of shedding light on the aforementioned convergences and divergences between the considered constructs. Therefore, we put the concept of "domain of validity" at the heart of our theory presented in the following section.

It is worth noting that the complementary nature of the constructs reviewed above has been asserted by many authors. For example, the authors of the *knowledge in pieces* perspective do not claim that all knowledge is structured as p-prims, but that this new perspective offers a previously undescribed level of knowledge structure and that an inclusive view admitting both *conceptual framework* and *knowledge in pieces* perspectives is likely necessary to fully explain student knowledge. This "federative trend" is carried by more recent research that is now attempting syntheses that explain disparate individual observations of difficult-to-change preconceptions (Brown, 2014; Chi, 2013; Hammer, 1996; Hammer, Elby, Scherr, & Redish, 2005; Taber, 2008).

3. Domain of validity-based preconceptions: a theory of action

The first and third author, as teachers at university level in an engineering school, have confronted students' learning difficulties apparently caused by prior knowledge. Our "exact science" background prompted us to try to model the observed phenomenon to derive an explicit teaching strategy to address these difficulties. Here we present a theory that is compatible with most of the concepts cited in Section 1 and reconciles some of the oppositions noted in Section 2. It includes a graphical representation of a cognitive shift not previously explicitly documented. As any model[3], it does not pretend to address all aspects of the phenomenon. After presenting and illustrating this model (based on two main hypotheses), we discuss its links with existing literature.

3.1. A first hypothesis about knowledge

In existing constructs, the *knowledge* or *conception* is typically considered to be the central (if not sole) element of the cognitive structure. This knowledge is typically considered right/wrong or naïve/expert, making the validity of the knowledge a binary value. We will refer to these two assumptions (knowledge is "atomic", and its validity is "binary") as the *monolithic view* of knowledge. Instead, we hypothesize that knowledge consists of *two* connected elements: a *model* and a *domain of validity* (or *DoV*). Both the model and the DoV are part of an individual's cognitive structure, hence their *knowledge*.

In engineering science, a model is a tool that allows its user to economically describe and predict real world behavior using abstraction. Confronted with the environment (*real-life*

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

experiments), humans need a way to reduce its complexity or *abstract* it. Thus, knowledge involves generalization: creating a set of concepts and principles that extract and formalize some regularity across individual situations, so we can communicate and reason about the world around us. We refer to such a set of concepts, principles or even set of equations as a *model*. The *model* is usually considered equivalent to *knowledge* in the previous constructs, thus we clearly propose a shift in definition.

In addition to a model, we claim 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 experiments (i.e. situations). We assume the DoV is also built by generalization and guides the *selection of* a specific model when facing a situation. However, we hypothesize that the DoV is more implicit and unconscious than the model, thereby explaining why the monolithic view (where the knowledge *is* the model) is so common.

Figure 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 real-life experiments. 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" real-life experiments, but not the "black-dot" real-life experiment. These "experiments" include situations students may face in everyday life as well as situations (e.g. exercises, labs, problems) created by the teacher.

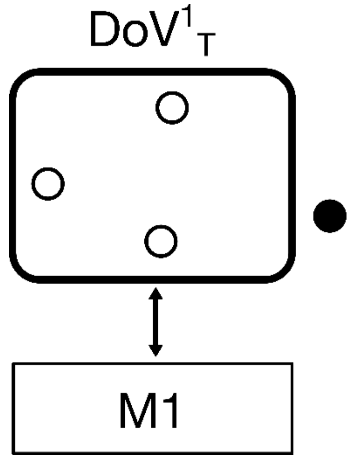

Figure 1 Knowledge is a model associated with a domain of validity (DoV)

Our first hypothesis has two important consequences[4]. Firstly, a model – assuming it reproduces at least one real-world experiment – 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 characterizing models as "right or wrong" or even "naïve or expert", as much of the literature discussed in Section 1 does. For example, Maxwell equations (model) represent very well a large set of real-life experiments of electromagnetic phenomena ("white dots"), but they do not represent the electrochemical reaction that occurs in a battery to produce the 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.

[4] 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.

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 situation. 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.

As a second example, the model of the Earth as flat is extremely useful and highly accurate when building a house, but disastrously inaccurate when launching a satellite. However, the flat Earth model is classically said to be "false" in class. Yet the contradiction doesn't come from the model itself, but from the failure to recognize and discuss models and their associated domains of validity. Introducing the DoV concept allows us to capture the fact that this model is sufficient in many circumstances, but not all circumstances.

This situation is depicted at the top of Figure 2 (representing the teacher's cognitive structure) where two models M1 and M2 are both valid but in different domains of validity.

In summary, the DoV is the (often implicit) part of the cognitive structure that describes the area in which a model succeeds in predicting real-world behavior. DoVs lead us to abandon the idea that a conception is "right" or "wrong" and opens the door to multiple valid conceptions coexisting. Explicit recognition of domains of validity is lacking in existing literature and teaching strategies derived from it.

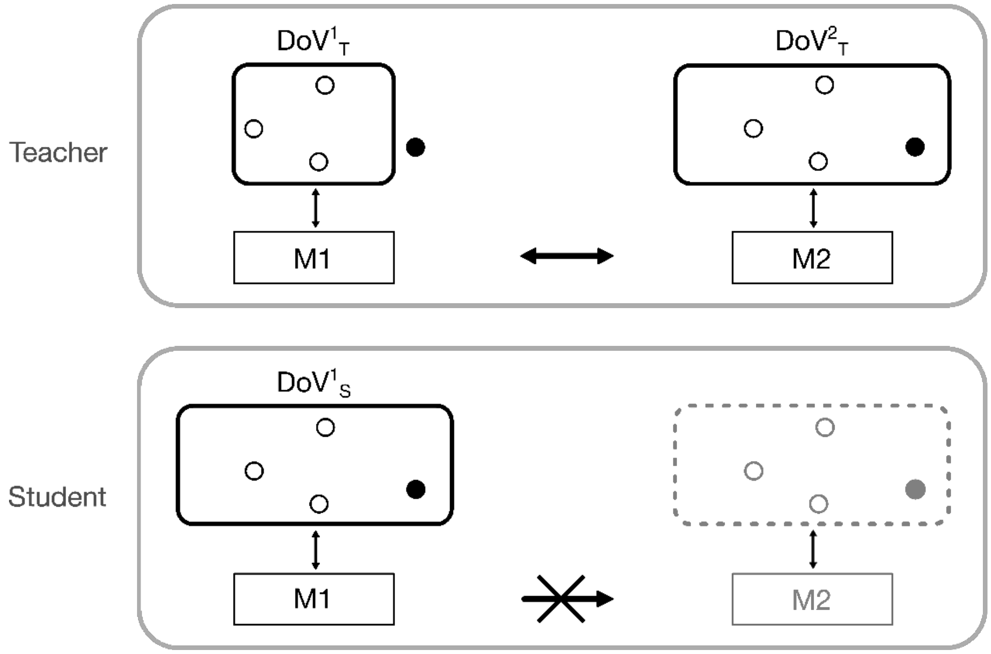

Figure 2 Graphical formalization of our framework

3.2. A second hypothesis about preconceptions

Our second hypothesis is that a preconception consists of an *overgeneralized DoV*: a domain of validity too wide relative to what the associated model can really represent. This simple hypothesis explains many phenomena related to prior knowledge. It also suggests that the typical blocking situation experienced in learning is due to the monolithic view of knowledge itself, held by the teacher and/or student.

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 experiment (black dot) is properly described by M2 but not by M1 (for instance, electromagnetic propagation compared to quasi-static (M1) or full (M2) Maxwell equations).

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 oversized DoV (here including the black dot experiment covered by M2). This cognitive structure could for example result from the following hypotheses: (1) The teacher, having presented "white dots" experiments 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 experiment yet; (3) the student, by generalizing these experiences, implicitly built an overgeneralized DoV of M1 since neither the student nor the teacher consider knowledge as having another component than the model itself.

When the teacher presents the students with a "black dot" experiment for the first time (for which M2 is a better fit), the students will use M1 according to their own cognitive structure (especially if the student is not conscious of a structural difference between this black-dot experiment and the white-dot experiments). According to the previous hypotheses, the student is confident in M1 because using it in the past has resulted in positive feedback from the teacher. However, in a classical true/false monolithic view, the students' answer is "wrong" because it does not include M2 as the teacher expects.

Even if the teacher explains M2 before presenting the student with the black-dot experiment, students may not be aware of the relevant DoV of either M1 or M2, as long as the DoV remains an implicit (or even a peripheral instead of central) component of knowledge. Thus, even when students say they have been exposed to and have understood M2 (a *model*), they may still try to solve black-dot experiments using M1, since these experiments are included inside their DoV[1]. Doing so is logical, especially when the teacher and student only talk about "right" and "wrong" models and not about domains of validity. Because DoVs remain implicit, teachers and students may not detect that their DoVs are not the same. Thus, this misalignment of DoVs (more than models) lies at the core of preconceptions.

For students laboring under the monolithic view of knowledge, the first encounter with the black-dot experiment will result in three simultaneous discordances:

1. At a cognitive level it is difficult to understand, in absence of additional elements, *why* M1 suddenly "does not work" when it has always worked before;
2. At an affective/emotional level, it may be upsetting when the model in which a student has confidence built on past experience suddenly doesn't work anymore. Students may feel a sense of betrayal, especially when a pattern of positive teacher feedback for use of M1 is broken. Insofar as a model is 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!
3. At an epistemological level, it is difficult to understand why one should throw away a model that works in practice.

When left unexplained, these discordances, may impede students' access to M2. In the monolithic view, the students should discard M1 ("erase it from memory"), although M1 has been coherent and successful with their real-life experience thus far (white dot experiments). In the absence of additional explanations (as, for example, the fact that M2 could be a superset of M1) "abandoning" M1 is paradoxical. Hence, we call the black-dot experiment the *paradoxical experiment*.

The discordances cited above are a consequence of the classical, monolithic view of knowledge. Our theory offers an alternative. 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 anymore” (in this situation, at this level of analysis or for this purpose). Moreover, the overgeneralization process that leads the student to build an oversized DoV for M1 is more likely if teacher and student 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 select an appropriate model when facing a real-life experiment (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. 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.

3.3. Overcoming the preconception

Following our propositions above, overcoming a preconception 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). What needs to be “abandoned” is only its use *in relation to* the paradoxical experiment. This awareness opens the door to considering a second model with a DoV that includes the paradoxical experiment.

Reducing the applicability of a model may seem counterintuitive when a key goal of teaching is to enable students to transfer knowledge, 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 focusing on the appropriate DoV associated with a model (i.e. finding new "white dots": real situations when the model is appropriate), but it emphasizes the *expansion* of a model's domain of validity. Overcoming a preconception involves *reducing* an overgeneralized DoV (i.e. excluding the "black dots": real situations for which the model is inappropriate). Therefore, our theory 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 theory suggests shifting from the model (preconception) itself to the domain of validity of a given model upon which an explicit teaching strategy may be designed.

3.4. Teaching strategies

We propose that teachers first make students aware of models and domains of validity and the tendency to overgeneralize DoV. Then, following a constructivist logic, present a paradoxical experiment in which students' application of an existing model will fail, leading to acceptance of the limit of the existing model and a search for a new model.

This principle of confronting students with a paradox has been proposed by others, including the predict-observe-explain (POE) strategy (White & Gunstone, 1992), demonstrate-observe-explain (DOE) strategy (Champagne, Klopfer, & Anderson, 1980), elicit-confront-resolve (ECR) strategy (McDermott, 1991), and the elicit-confront-identify-resolve-reinforce (ECIRR) strategy (Wenning, 2008). Our model uncovers the mechanism underlying these teaching processes – by shifting the focus from the knowledge (mental model) itself to the associated DoVs.

When teachers face an “error” (and more specifically a recurrent and difficult-to-overcome “error”) from one or several students our proposal suggests, for example, the following strategy (in oral discussions such as lectures, seminars or laboratories):

1. Listen to the students (possibly using additional questions) to identify the model(s) and the DoV(s) included in their cognitive structure;
2. Having identified the elements in Figure 2, create a paradoxical experiment (i.e the “black dot” experiment) that falls outside DoV^{1} but inside DoV^{2};
3. Make students confront the result of the real-life experiment prompting reasoning/prediction using model M1, creating cognitive conflict.
4. Without discarding M1 itself, push the students to continue to reason logically and confidently about the situation to explain precisely where their conflict resides. Guide them to the point where they formulate (often in the form of a question), a way to solve the contradiction.
5. Confirm the elements (concerning the models, the DoVs, etc) in accordance with M2 contained in the student’s proposals, reinforcing the student's confidence where appropriate. Teacher confirmation will help students to think “outside” their usual representations (M1) in order to build M2. Help the student to realize that M2 is a better fit with the real-life results than M1.
6. Confirm the new model is valid, and resolve (or ask the student to resolve) the coexistence of the two models by linking them explicitly.

In this procedure, a key point is to push students to consider the situation from a different perspective than the previous view, using their own reasoning. To imagine the M2 model, students must feel safe in expressing "strange" ideas. A monolithic view of knowledge can block such exploration.

While the example above is one of dialogue, there are other ways to guide students through the key steps. For example, a written exercise for an entire class may focus on common cognitive structures (from past examinations, for example), creating an appropriate paradoxical situation and confronting students with it via Predict-Observe-Explain (White & Gunstone, 1992) sequences. We used such a strategy in circuit theory sessions in an engineering course with a significant increase (from 50% to 75% success rate) in the students' results (Sommeillier & Robert, 2016, 2017, 2018).

4. Our theory as an integrative step

4.1. Ideas and issues

In Section 2, we highlighted several oppositions found in the existing literature reviewed in Section 1. Each of these oppositions in the six key constructs are explicitly integrated into our theory of overgeneralized DoVs.

One opposition is whether prior conceptions must be removed to reach expert conceptions (*misconception*) or can be positive and useful on the way to accessing a new model. Introducing a two-component view of knowledge (model plus domain of validity) allows both of these perspectives to be true. The model is useful and needs to be retained, while the domain of validity needs to be altered.

Another opposition is between a discontinuous versus continuous view of learning. According to our theory, 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, an overgeneralized M2 may be the next preconception. 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. Discontinuity is found (1) in restricting the DoV of the initial model but more importantly (2) in accessing a new model (M2) that allows a new interpretation of the world and (3) making links previously unknown between this new model and the initial one.

The idea that prior knowledge may result in a troublesome learning experience when facing the paradoxical experiment (Figure 2) has been linked to three different types of discordance (cognitive, affective and epistemological) endemic to the monolithic view of knowledge. Moving from a monolithic view of knowledge to one that incorporates both a model and its domain of validity accommodates the various key ideas contained in existing literature and resolves the oppositions between different constructs. As such, adopting a two component view of knowledge mitigates all three discordances.

4.2. Reinterpreting existing key constructs

Our theory of action uses a small number of concepts: *knowledge*, *model*, *domain of validity* (as a part of an individual’s cognitive structure) and *real-life experiments* (including *paradoxical experiments*). 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 theory 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 our theory.

Preconception. In Subsection 1.1, we interpreted from the literature 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.

According to our theory, we propose a two additional defining features of *preconception*: (5) knowledge is the association of a model and domain of validity; (6) preconception is knowledge containing an overgeneralized domain of validity that includes experiments 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 experiment.

Misconception, alternative conception and anchoring conception. We reject the term *misconception* because it suggests knowledge may be intrinsically false and should be removed, which contradicts our first hypothesis (Subsection 3.1). *Alternative conceptions* and *anchoring conceptions* 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. The *p-prim* is more difficult to express in our theory. 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.

Both of these elements are compatible with our theory, 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")*, though it does not explicitly explain the association between models and domains of validity as our theory does.

Troublesome knowledge and threshold concepts. According to our theory, 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, largely assuming a monolithic view of knowledge. Our theory offers a different explanation for why some target conceptions are "troublesome" for students.

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). Moreover, concepts are components of models, so a "threshold concept" remains fuzzy.

Nonetheless, our theory is consistent with the five key characteristics associated with *threshold concepts* (see Subsection 2.4). The property of "boundedness" 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 experiment is likely to be troublesome and once a new model is introduced (shrinking the DoV 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, our theory 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 theories, a *cognitive obstacle* is an initial model present in the student's mind acting as an obstacle to new knowledge. In our theory, the element preventing access to a new model is not so much the model, but the overgeneralization of the domain of validity of the initial model.

Referring to Piaget's definition (Subsection 2.5), *cognitive conflict* is the discomfort experienced by a student originating from various discordances as described in Subsection 4.2. In our theory, Piagetian *cognitive conflict* is stimulated by a *paradoxical experiment*.

Finally, *cognitive rupture* is the transition from an initial conception to a target conception. In our theory, it corresponds to a series of ruptures leading to the target conception: (1) understanding that the initial domain of validity was overgeneralized (for instance by considering differences between black dot and white dot experiments) 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, our theory accounts for and resolves discrepancies between a number of existing constructs in the literature.

5. Discussion, limitations, further work and conclusion

By embracing a two-component view of knowledge and explicating the domain of validity of various models, we propose a new theoretical framework useful to both understanding and addressing difficult-to-change prior knowledge. Our model explains the obstacle to learning as an overgeneralized DoV. We propose an instructional technique in which students confront a paradoxical situation so that the student realizes the limits of the original DoV and subsequently both searches for a new model and reduces the domain of validity of the original model. This instructional model also emphasizes the importance of teaching not just models, but their domains of validity. This instructional model, then, also means being explicit about the two components of knowledge.

We have demonstrated the integrative power of our theory in relation to six scientific constructs related to prior knowledge, firstly by resolving apparent oppositions between these constructs, and secondly by redefining (or at least linking with our model) known terms using a small set of 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 theory 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 we have given an example from and tested the theory in our field of electrical engineering (Sommeillier & Robert, 2016, 2017, 2018), further research is needed to demonstrate its broad applicability across fields of science, the effectiveness of different teaching strategies based on the theory, the relationship with other theories such as p-prims, and the socio-cultural, emotional and affective dimensions of overcoming DoV-based preconceptions.

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