Reconceptualising the Learning and Teaching of Scientific Concepts

Colette Murphy

Introduction

In a recent discussion with physicist colleagues about ways to address high attrition rates for first year undergraduate science courses (see, for example, Matz et al. 2012) the subject of difficult science 'concepts' arose. We argued about the nature of concepts and whether they actually existed or whether they were human constructs, developed in attempts to explain natural phenomena. One physics colleague, Jack (pseudonym), found this disturbing: "What about *magnetic flux density* then, are you saying it's not real?" We discussed assertions that scientific concepts could be theorized as *tools*, constructed using scientific investigation and that some are better than others for use in explaining specific phenomena and that all can be refined. Jack was disturbed, and said he needed to go away and think hard about this.

This chapter explores the use/misuse of scientific concepts in teaching. It attempts to provide an action-oriented view of concepts as dynamic, changeable, contextualized and usable *tools* that have been developed over time to help explain the world around us and how it 'works'. Learners and teachers can critique these tools: Are they all 'good'? Which ones are fit-for-purpose? Have all been demonstrated definitively to exist, or are some still models (the atom?)? It considers the work of Vygotsky and his followers, among others, and suggests ways in which students and teachers can think differently about learning and teaching science concepts in school and undergraduate science classes. Vygotsky's work helps to address many questions relating to scientific concepts and their development.

Vygotsky (1896/1934) lived until he was just 37 years of age, yet his legacy continues to affect learning and teaching 80 years after his death. Science education researchers recognised the significance of Vygotsky's work for transforming the

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C. Murphy (✉)
Trinity College, Dublin, Republic of Ireland

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learning and teaching of science around 20 years ago (Driver et al. 1994; Howe 1996; Lemke 2001; Wells 1994). More recently, citations of Vygotsky in science education journals have increased significantly, although there is little evidence of researchers reading Vygotsky deeply and applying his constructs systematically in research and practice. For instance, Lima et al. (2014) cite a handful of studies in which “meta-theoretical commitments to dialectical materialism have been put to work as tools for original theorization in various sensible different situations” (p. 562). These four studies include those of Wells (2008) and Murphy and Carlisle (2008). This chapter is based on a close reading of Vygotsky and other scholars’ work on concepts and how such ideas can help science learning and teaching.

Currently, many scientific concepts are presented as ‘entities’ to be ‘learned’ and are difficult to transfer to everyday and current science research and practice contexts. In this chapter I revisit learning science via a sociocultural perspective, in which science learning and teaching is not organized for a ‘generic’ learner, but is structured to support the learning and contributions from diverse learners (see also Reiss, this volume). Learners and teachers use scientific concepts collaboratively in meaningful contexts, promoting science as asking questions and searching for explanations of phenomena, which is not always straightforward. Firestein (2013) describes the process of scientific endeavour as akin to looking for a black cat in a dark room, and there may not even be a cat in the room. His advice for getting the feel of how scientists think is:

> Next time you meet a scientist — at a dinner party, at your child’s school, just by chance — don’t ask her to explain what she does. Ask her what she’s trying to figure out. (p. 82)

The notion of *using*, as opposed to *learning* scientific concepts, underpins much of the argument in the chapter. This idea arises from writings of Vygotsky and Wittgenstein; the latter suggested in his later corpus that the meaning of concepts lies in their *use* in particular contexts. The idea was also key to the discussions of the ‘ordinary language’ philosophers of the mid-20th century, who suggested that it is more fruitful to *use* high-level concepts (e.g., time) than to try to define them. We can then define lower-level concepts (e.g., watch) only because we are able to use the higher level concept on which it depends. It is common, however, in science classrooms for teachers to expect students to learn specific definitions of concepts (e.g., energy) outside of a context, instead of considering the different ways the *idea of energy* is used both within and outside science. I will be advocating ways that we can engage students in their learning more positively if we loosen our reliance on considering concepts as universal, permanent entities.

An outline of the ideas in the chapter is presented in Table 1. The chapter is constructed in three main sections: the nature of scientific concepts, how they develop, and classroom research into scientific concept development.

Table 1 Moving towards a sociocultural view of scientific concepts

Traditional	Sociocultural
Nature of scientific concepts (SC)	
SC exist as entities	SC are created as **tools**
SC represent 'truth'	SC created in scientific endeavour
SC are independent of culture	SC are culture-dependent
SC are universal	SC are context-bound
SC are permanent	SC are subject to change
Ideas and theories of scientific concept development	
Maturation is the driving force of development of SC—abstract concepts develop later	The social world is central to and mediates the development of SC—toddlers use abstract conceptualisation in play
Development leads learning of SC	Learning leads development of SC
SC develop linearly	SC development is dialectic and occurs via the ZPD (see Fig. 1)
The development of SC is progressive	Development of SC comprises zigzags, gaps, regression, and conflicts
Students' SC are either correct or 'misconceptions'	Students' SC represent their best try at explaining phenomena
SC development occurs when misconceptions are challenged via cognitive conflict	SC development occurs via thinking in complexes and pseudoconcepts
SC development is independent of emotion	Development of SC requires emotion
Classroom research on scientific concept development	
Teachers create science content for children to learn SC, based on curricular guidelines	Children learn meaningful science oriented within four major concepts: place, time, materials and conscious reflection
Verbalization of SC is assessed as learning	***Use*** of SC is assessed as learning
Logical SC 'grow' from experience	Learning of SC requires bridging into scientific convention
SC are learned independently, e.g., via IBSE	Learning of SC is mediated via cultural tools, including language, signs and symbols
Children learn SC individually	Children learn SC socially
Learning SC does not require student dialogue	Learning SC requires forms of dialogue
Learning of SC is reactive to the teacher	Learning SC occurs via dialogue and problem-solving
SC are 'created' by the teacher for students to learn	SC are co-constructed by students and teachers
Primary science requires children to learn basic SC	Primary science provides opportunities to derive scientific explanation from close observation
SC taught over a short period	SC are developed over a long time
The direction of learning SC is bottom-up	The direction of learning of SC is top-down

The Nature of Scientific Concepts

Most definitions of a scientific concept refer to it as an idea, or law, which helps to explain a phenomenon under investigation. Taxonomies have been developed, but none of these have generated wide acceptance—it is difficult to reduce the levels of complexity into a single framework. Definitions can limit the scope of scientific concepts in that they exclude the entire *process* of scientific endeavor. What about the concept of *inference*, or indeed *investigation*? Voelker (1975) suggested that such concepts are themselves major scientific concepts that need to be included within a broader definition. But how so?

For educational purposes, Vygotsky proposed a 'super-concept' framework that defines all human activity within the environment. There are four major concepts in this framework (Kravtsova 2010):

- *Time*—all human activity in the world occurs in a certain time;
- *Space*—all human activity takes place within a space, or place;
- *Substance*—all human activity uses substance, or materials;
- *Conscious reflection*—human activity differs from other animals because of the element of reflection on what, how and how to improve the action or activity.

It could be argued that this framework provides a structure in which every scientific concept can be subsumed. We can find a place for the 'process' concepts within Vygotsky's framework under 'conscious reflection'.

Theoretical Considerations of the Nature of Scientific Concepts

In his theoretical consideration of concepts, Vygotsky used a model from classical mathematics that suggests that ultimately concepts are all subsumed into one logical system, which he refers to as a system of equivalences:

> The higher levels in the development of word meaning are governed by the law of equivalence of concepts, according to which *any concept can be formulated in terms of other concepts in a countless number of ways.* (Vygotsky 1934/1986, p. 199, emphasis in original)

His broad grid for concepts is based on the surface of a globe, onto which every concept can be placed using a system of coordinates, corresponding to latitude and longitude in geography. A concept's 'longitude' relates to its degree of abstraction, and thus characteristic of thought processes, while its 'latitude' represents its objective reference, for example: plant or animal.

The geographic analogy is only useful at a surface level, however. Vygotsky himself emphasised the limitation of the geographic analogy as being neither complete nor accurate, although it has been used since, particularly in philosophical considerations of concepts, such as in the work of the ‘ordinary language’ philosopher, Gilbert Ryle. Vygotsky contended that in a *true scientific concept*, the bonds between the parts of an idea and between different ideas are logical; thus the ideas form part of a socially constructed and accepted system of hierarchical knowledge (Berger 2005).

Science Concepts as ‘Tools’

More recently, as the field of science education has embraced sociocultural theory, the idea of scientific concepts as ‘tools’ for use in helping to explain and understand phenomena has become much more accepted. Wells (2008) argues that scientific concepts are not possessed by individuals; rather they provide cultural resources, which are used for a variety of purposes. Thus, scientific concepts can be considered as ‘cultural tools’ developed by scientists, to help describe and explain the world around us. Mastering their use, Wells suggests, is best developed when students are engaged in scientific problem solving, which requires these ‘tools’.

Vygotsky first developed the notion of *cultural tools* via a dialectical synthesis of the thesis that human cognition developed through the use of physical tools (made, for example, from stone, iron and bronze) and the antithesis that human cognition developed via the use of communication. His synthesis of these two arguments was to suggest that human cognition developed from a combination of tools and communication: the development and use of *cultural tools*, the main one of which is language. Cultural tools are the signs and symbols that comprise the mechanism for the development of higher cognitive skills, or, in today’s parlance, *thinking skills* (Gredler and Clayton-Shields 2008). They include graphs, charts, symbol systems and language. When humans first made use of physical tools, they communicated with each other ways that the tools could be best used for various purposes (gestures, etc.). Thousands of years later, speech evolved and ‘knowledge’ became stabilised as ‘cultural tools’ (for instance, descriptions of tool use in different contexts) within oral tradition, which was passed to subsequent generations. Vygotsky argued that human cognitive development is different from animals in that it is largely, although not entirely, based on language (van der Veer 1994). This collective memory, or knowledge, was externalised with the invention of writing. Knowledge was more permanent and thus independent of who produced it, and became written ‘objects’ used for education in different cultures (Wells 2008). Knowledge was thus passed on via collaborative activity using cultural tools, such as pictures, diagrams and writing. As science developed, concepts were created, based on empirical observation and thorough scientific investigation, to help explain phenomena.

Here we have a much more *active* description of scientific concepts. They are constantly being tested for their ability to function as tools in different contexts. Some tools are better than others at doing a specific job. It could be the case that some scientific concepts serve the science context well, but not the science education context—for example, respiration. The term 'respiration' is confused with breathing by younger learners, and the biochemistry of respiration is far too difficult for most senior school biology students to understand, unless they have a good knowledge of chemistry. Some concepts are very tricky to use, especially if there is complex mathematics involved, such as relativity theory. Are the scientific concepts we use in schools for science learning fit for purpose? Or is the question: is the *way we teach* science concepts fit for purpose? It can be useful for students to be made aware that each scientific concept has been generated during the investigation of specific contexts and then replicated to test its generalisability. Science concepts are not permanent, however; they change with time and new technologies. Fensham's chapter (this volume) argues for learners to become connoisseurs of science. His ideal can be developed in school science with increased attention to discussions of how, where and when various scientific concepts came about, including the associated difficulties, political and technological barriers and enablers, as well as other human factors, to engender a deeper appreciation of the scientific endeavour.

Development of Scientific Concepts

The way(s) learners develop scientific concepts has been debated for many years. Conceptual change. Has become very popular in recent years; it was believed that students suffered 'misconceptions' about phenomena and in the process of cognitive conflict when they were challenged with the scientific explanation, they went through a process of conceptual change, drawing on their growing science knowledge and that of teachers and peers (Hewson et al. 1998).

Conceptual change, however, has not delivered the learning gains needed, for example, university physics students still misunderstand very basic concepts as evidenced by consistent poor performance on the force concept inventory test (Miller et al. 2013). Miller et al. look to different explanations as to why some scientifically wrong ideas persist at university. They suggest that unless learners are *using* scientific concepts in, for example, problem-solving, it is unlikely that they will retain the scientific explanations they are presented with after they have learned them for a test or examination. It could be that such scientific concepts are not good for learning out of context and that we need to apply different pedagogical approaches to affect the understanding of specific concepts.

Another factor that is becoming increasingly important in science conceptual learning is the role emotion plays. Vygotsky proposed the importance of the *unity of affect and intellect* in the zone of proximal development ZPD—that emotion and learning are interdependent. It is impossible to learn without emotive engagement (Reid 1788/1969) and other higher mental functions (Mahn and John-Steiner 2002). Matthews' chapter (this volume) provides more discussion of the crucial role of emotion for science learning.

The rest of this section summarises research into scientific concept development in children over the past century. Perhaps the strongest idea to come from this work for today's science classrooms is the prevalence of pseudoconcepts in science learning—students can repeat the scientifically correct concept to gain examination credit without understanding its nature or being able to apply it.

Very Young Children Use Abstract Thought

Children are capable of abstract thought from a very young age. Vygotsky suggested that children's imaginary play is key to their ability to abstract. For example: a child playing with a cardboard box and using it as a 'shop' for play purposes—the child affords the box certain characteristics of 'shopness' during the game. Imaginary play is not often seen in the classroom science in many schools; most 3–5-year-old children are playing like toddlers, just manipulating objects, such as sand and water, and not engaging significantly with other children (Murphy 2012).

Vygotsky maintained that creating an imaginary situation in play provides a means by which a child can develop abstract thought. Children develop abstract thinking via the use of objects—for example, toys, props, clothes—in make-believe play. Such a use of objects for pretend rather than real-life purposes serves as a bridge between the sensory-motor manipulation of objects and fully developed logical thinking, when the child can manipulate ideas in their heads. Using various props to separate the 'meaning' of the object from the object itself. For example, to drive a block on a carpet as is it were a truck (giving the block 'truckness') acts as a precursor to abstract thought. The best kind of play to develop abstract thought is where children use unstructured and multifunctional props, as opposed to those which are realistic. Non-realistic props strongly promote language development to describe their use. For example, a cardboard box may serve first as a shop, then as a school, then as home. Vygotsky suggested that this repeated naming and renaming in play helps children to master the symbolic nature of words, which leads to the realisation of the relationship between words and objects and then of knowledge and the way knowledge operates.

Vygotsky's perspective on play also connects it to the social context in which a child is brought up. He maintained that adults and older children should also be involved to enable the younger children to model both roles and the use of props. Vygotsky promoted the notion that play, as learning, should lead development, as opposed to the more accepted one of development leading learning or play. Veresov (2004) discussed learning that takes place in or within children's play. He used the Vygotskian example of a child playing with a stick by using it as a horse. The child will learn about the object (stick) and its objective physical properties, but she/he will also decide whether such properties allow or prevent the stick from becoming a horse. If the object does not suit the play task, the child will stop playing with it.

In primary school science, a Vygotskian perspective would presuppose that teachers promote role-plays and imaginary play in science learning for children throughout the primary school to further the development of abstract, conceptual thought. There would be a lot less focus on individual play with objects and more on collective play, preferably involving older children who can model both roles and the use of props for the younger ones.

Concept Development Is Dialectical, Not Linear

Vygotsky (1934/1986) proposed a dialectical, as opposed to a linear, model for the development of scientific concepts: "the child's scientific and [her or] his spontaneous [everyday] concepts… *develop in reverse directions* …they move to meet each other" (p. 192, emphasis in the original). Using the example above, the students' everyday concept of a *puddle* develops more scientifically when they learn about evaporation; at the same time, their concept of *evaporation* will become more everyday to them when applied to familiar contexts, such as puddles and perspiration.

Vygotsky proposed that teachers create a *zone of proximal development* (ZPD) between the scientific and everyday concepts by illustrating and emphasising the *relationships* between them and showing how the scientific concept can be utilised to explain the everyday concept, while simultaneously raising the everyday concept towards its scientific conceptualisation (see Fig. 1). For instance, a child may have a rich understanding of the everyday concept *brother* but not be able to define it in the more logical, conceptual way as *male sibling* (Panofsky et al. 1990). The task of the teacher, for Vygotsky, is not to evaluate individual conceptions as correct or as 'misconceptions', but rather to help the child, through instruction with respect to the *relationship* between concepts within a system of concepts, and to develop conscious awareness and voluntary control of her/his own thinking (Wells 2008).

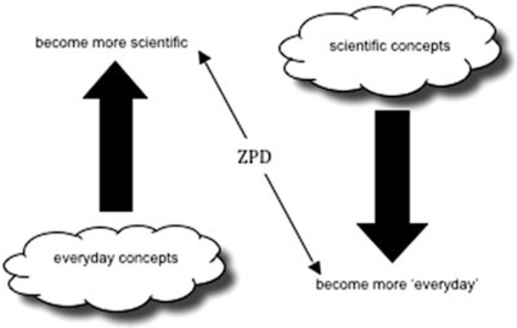

Fig. 1 Dialectical model of concept development

The Process of Forming Scientific Concepts

Most of the science education research literature regarding scientific concept formation relies on the work of Piaget (1955, 2001) and Vygotsky (1934/1986) and their followers. The general argument is whether (a) it occurs via replacement of child (egocentric) concepts by adult ones as children get older (Piaget) or that (b) scientific concepts are formed from learned experiences in which children first exhibit ‘pre-conceptual thinking’, which shows evidence of organising thoughts and some abstraction, but not of systematic thinking or sophisticated abstraction.

Over two decades ago, I argued that both of these explanations underestimated young children’s thought in terms of coherence and systematic thinking (Murphy 1987). The study involved 280 children (5–7-year-olds) who were recorded during a game in which a child described the meaning of a scientific word (concept) without using it for the rest of the class to guess the word. Despite a large proportion of the responses being context-bound, children’s descriptions evidenced definite, coherent ideas about most of the concepts. Many 7-year-olds demonstrated a level of abstraction beyond that predicted by Piaget or Vygotsky. For example: the description of *amount* as *degrees*; *weather* as a *sort of condition*; *transport* as *types of vehicles*, and *idea* as *a plan*. I argued that the limiting factors in the development of scientific concepts could be largely related to lack of vocabulary, experience and specific conceptual frameworks, as opposed to the lack of systematic thinking.

The Vygotsky Blocks Experiment

Vygotsky and his co-workers explored the process of concept formation using a series of *double-stimulation* experiments. Double stimulation is a principle according to which a subject, when in a problematic situation, turns to external means for support in order to be able to act (Vygotsky 1997). The problem is the first stimulus and the external means is the second stimulus. Vygotsky’s double stimulation method placed learners in problem-solving situations that were different from any learning they would have experienced. The experiments thus investigated the formation of *new* concepts via problem-solving tasks requiring the use of non-verbal *signs*. The signs provided a way to solve the problem (Sakharov 1928). Vygotsky and his co-workers studied the ways that learners of different ages struggled or successfully used these aids, documenting changes in learner activity and accompanying changes in cognitive functioning. The task was to sort a set of wooden blocks of different colours, shapes and sizes into four groups. The experiment was repeated more recently by Towsey (2007), who described the blocks as follows:

> The material comprises 22 wooden blocks of five colours (orange, blue, white, yellow, and green); six geometric shapes (isosceles triangles, squares, circles, hexagons, semi-circles, and trapezoids); two heights; two sizes (diameters); with the labels **cev**, **bik**, **mur**, and **lag** written underneath them (**lag** and **mur** having five blocks each, and **cev** and **bik** having six). (p. 3)

The labels in Towsey's description represent the signs that provide a way to solve the problem. There are four labels and four groups. At certain points while working on the task, the participant is invited to look at a label and see if the clue aids its solution. The solution is that the *lag* blocks are all tall and big; the *mur* are tall and small; *bik* are flat and big; and *cev* are flat and small.

The blocks experiment formed part of a series carried out by Vygotsky and co-workers, which led to the proposal of the stages that are passed through in the formation of concepts by children. The stages comprise *random grouping*, *thinking in complexes, pseudoconcepts* and *true concepts* (see Fig. 2).

The youngest children grouped objects 'randomly', according to chance or some other subjective impressions. Older children demonstrated that they were thinking in complexes, in which they began to abstract or isolate different features, or attributes. These were related to the child's experience, not using logical thinking. At this stage the child is showing evidence of organising thoughts, which lays the foundation for more sophisticated generalisations. Such pre-conceptual thinking is deemed necessary for successful mathematics (Berger 2005) and scientific concept construction. The next stage is the development of pseudoconcepts, which can be confused with true concepts because the learner might be using the right words to describe the concept, but lacking the logical connections between its parts. The learner is able to use the pseudoconcept in communication and activities, such as exams, as if it were a true concept. For example, the learner may use the definition of an ionic bond to describe how it differs from a covalent bond without understanding the nature of chemical bonding. The words of the learner and teacher may refer to the same idea, but their meanings may not be the same (Gredler and Clayton-Shields 2008). Berger (2005) suggests that true concepts are formed from pseudoconcepts via the *appropriate* use of signs and social (frequently teacher) interventions, thereby forming a bridge between the individual and social meanings.

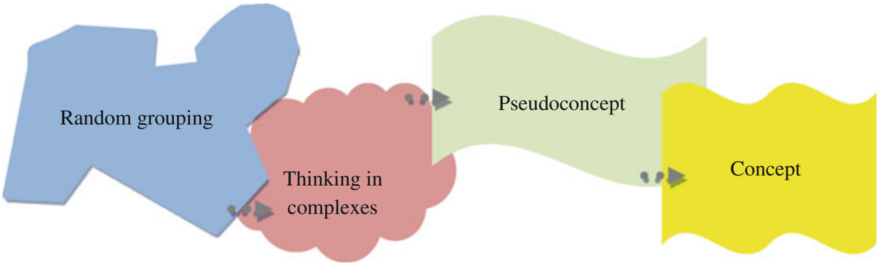

Fig. 2 Scientific concept formation stages

A true concept is bound by *logical* bonds within parts and between different concepts.

The Prevalence of Pseudoconcepts in Science Learning

Many students pass science exams using pseudoconcepts, and only develop the full meaning much later, if at all. The teacher or exam marker may wrongly assume that there is no need for further development.

This confusion between identification of pseudoconcepts and concepts accounts for the common experience of pre-service science teachers that they only begin to understand science when they start to teach it. They might have used personally meaningful pseudoconcepts to communicate knowledge successfully using the written form, including appropriate use of signs, symbols and scientific terminology. But this may not have been as useful when trying to explain a similar idea without the 'props' of the signs and symbols. It could also explain the experience of tertiary students who find that many professors who are experts in their field can give excellent lectures in language they can all understand, whilst less expert academics frequently hide behind terminology and complexity. True concepts are learned with conscious awareness (Gredler and Clayton-Shields 2008) and promote the development of everyday concepts into the accepted scientific framework, where they can be used, further developed and critiqued.

A major problem in concept development is recognition of when true conceptual thinking is being demonstrated. Unless this process involves evidence that learners are *using* the concept(s) appropriately, it could be argued that it is a pseudoconcept, not a true concept. Another issue is the case that learners can be thrust into problem-solving with new concepts before they have developed them sufficiently for the task, resulting in incomplete concept formation. The eventual formation of true concepts indicates that the learner is now able to master their own thinking. One of the most difficult tasks for learners, according to Gredler and Clayton-Shields (2008), is to learn the connections and relationships between concepts. Their advice is for students to construct a large visual diagram of the concepts in the topic, and between topics, as the term progresses. This activity requires pre-planning by the teacher to identify the required concepts for learning in advance.

The ZPD in Scientific Concept Development

The ZPD represents the total interactions between the learner and others and with their environment, which need to take place between subsequent stages of development in, for instance, the learning of particular scientific concepts. The 'zone' therefore represents the 'buds' or 'flowers' of learning, leading to the 'fruits' of the next stage. Vygotsky first described the creation of ZPDs in terms of levels of assistance given to learners of the same ‘actual’ cognitive level (for example, same IQ scores) in solving more difficult tasks. Despite being measured at the same level, one child might solve the task with very little help (the support is thus within her/his ZPD for the task), while another may not solve it even after several different interventions designed to support the learning (the support is outside the learner’s ZPD for this task). Such interventions may include: demonstration of the problem solution to see if the child can begin to solve it; beginning to solve it and asking the child to complete it; asking the child to solve the problem with the help of a child who is deemed more able; explaining the principle of the needed solution, asking leading questions, analysing the problem with the child, etc. (Gredler and Clayton Sheilds 2008). Vygotsky considered performance on summative tests as an indication of the child’s past knowledge and argued “instruction must be orientated towards the future, not the past” (Vygotsky 1934/1962, p. 104).

Vygotsky’s later work, as well as that of his followers and other scholars, has extended ZPD creation to include a much broader range of interventions, including changes in the learning environment, selecting tasks to promote scientific thinking, and enabling meaningful scientific dialogue between peers and teachers. All of the examples of classroom research in the next section focus on ZPD creation to facilitate the learning of scientific concepts as tools, as opposed to entities.

Classroom Research in Scientific Concept Development

In teaching scientific concepts, we aim to: develop student understanding of the concept(s), make the learning meaningful in relation to school and out-of-school experiences, and enable students to appreciate and *interact* with the world of science, which uses concepts in codified and regulated contexts. The third aim is most neglected and yet, it could be argued is the most vital for engaging students to think and learn about the world as it is and its future. Below I provide some classroom research examples of how scientific concepts can be used in more interesting, dynamic and active ways in learning and teaching science.

ZPD Creation to Enhance Children’s Meaningful Science Learning

There are a number of experimental schools in Russia, designed on Vygotskian principles, called *Golden Key* schools (for details, see Kamen and Murphy 2011). In these schools, experiments, hands-on experiences, readings and discussions about science during the ages of 3–10 are considered foundational to true scientific thought, especially when children are encouraged to *theorise on their experience of* *observed phenomena*. In the *Golden Key* schools, ZPD creation to enhance children's meaningful learning is facilitated by mixed-age teaching, paired pedagogy and situating children's learning in a context that is meaningful, interesting and that motivates them to learn.

To facilitate children's experiences with and development in their thinking about science (as well as the other academic areas) the *Golden Key* Curriculum has a 4-year cycle of themes, based on Vygotsky's four super-concepts:

- Space (or place)
- Time
- Substance (or Material or Matter)
- Reflection

Place

When children start school at the age of 3, 'place' is the first concept focus. They are 'oriented' first in a group 'place' within the room, then in their own place within that group. They begin their exploration of place by working with the teachers to 'set up' the room. They bring in artifacts from home, including photographs, small ornaments, etc., which are placed on each child's table area and thus link the school place with the home place. Older children then take the younger ones around the school and gradually introduce them to the whole school and all who work there, including the other teachers and catering and cleaning colleagues. Early work with maps includes showing how to find other rooms in the school. When children are totally familiarised with the school, they reflect on this learning by inviting parents and relatives to the school, and children give them a tour of the school and its community. The 'place' orientation continues as children develop by orienting themselves between home and school, then in the local area, etc. Each classroom has a set of large wall maps, superimposed upon each other, so that children can orientate all of their learning in the 'place'; behind a map of the town (in the school I visited) was one of the province, behind this a map of Russia, then Europe and so on until the maps at the back were of the cosmos.

Teachers support children's ongoing exploration of place by creating imaginary journeys connected to the event that serves as the core of the lesson. These multi-age imaginary expeditions provide opportunities for children to engage in science learning. Teachers provide a context for older and younger children to explore life, earth, and physical science concepts. They set up imaginary interactions with science phenomena during the children's "travel". As they go on their "journey" they may look, for example, at which side of the rocks the moss grows or where the sun is—developing a connection between the moss and the sun, helping them develop a powerful understanding of scale. Older children may discuss these connections with the younger children. Children are introduced to, for example, the three states of matter by “encountering” water as steam, water, and ice or snow in their adventure.

Time

Similarly, children are oriented within the concepts of time, materials and reflection. Figure 3 shows a timeline, which children constructed as a ‘time-based’ activity for their own classroom. Their timelines start with the beginning of life on earth, and children can orient their science learning in time using them. For instance, they can mark the times when dinosaurs roamed the earth, the discoveries of fire, the wheel, electricity, the Moon landings, etc. They can use the timeline to visualise life spans of large trees, humans and elephants and to consider themselves in relation to older members of their family, ascendants and younger members. During the study of time the school creates a “time machine” and during their “time travel” they become aware of great scientific discoveries. They realise there was a time before electricity was harnessed and explore a time with no cars and where horses and candles were used instead of cars and electric lights. The goal is to help children to experience, in imaginary play situations, life before these discoveries. The time machine also “takes” children to the future—allowing children to use their spacecraft to travel to planets, solar systems, and galaxies. They explore flora and fauna. Through their imaginary travel, they investigate the cosmos and compare it to Earth. For example, children may compare the atmospheric pressure, surface temperature, and length of day on Venus to Earth.

The placement of the present day in terms of their cultural historical context is viewed as important to allow and facilitate the children’s mediation with their world and in turn promote development. As with the children’s interaction with space, the imaginary and real interaction with time by a multi-age group, and with the support of teachers, provokes development and foundational (both real and imaginary) encounters with science concepts.

Fig. 3 Timeline to help children orient their science learning in ‘time’

Substance

In relation to the ‘substance’ concept, children use materials in different ways depending on their age. Early exploration of materials is important for speech development. As children get older they focus on manipulating a wide variety of materials and theorise on these experiences to arrive at logical explanations of phenomena. Vygotsky maintained that children at elementary level need to be encouraged in such activities for science learning, which are vital for the later development of conceptual thought within the concepts constructed by generations of scientists. This world of science has its own ‘culture’ based on specific scientific tools such as signs and symbols, into which children will be encultured mainly at a later stage of their development (post-11) when they are taught by scientists or by teachers who have a good knowledge of science. The early theorising about children’s observations of phenomena is also how children become oriented within a framework of ‘reflection’. They are invited to present their ideas to other children and their teachers and to listen to and incorporate other ideas into their own reflections.

Reflection

During the 4th year, the year of reflection, these scientific methods and concepts switch from becoming the focus of science to the method of understanding and comparing and understanding different cultures. All the children have partially formed scientific understandings: emerging concepts that become more complex as they get older. The science study becomes more focused as an academic subject. An experiment is typically conducted with the whole (multi-aged) group at a *Golden Key* school. The older children also discuss experiments in their separate class period. Then they come back to the whole group, and with the teachers’ help, discuss the experiment with the younger children. Science becomes more formalised, with experiments providing the context for the older students’ science ‘reflections’. This formalisation through the students’ theorising at multiple developmental levels prepares them for more abstract and generalised understanding in middle school.

Creating ZPDs to Bridge IBSE with Scientific Convention

Inquiry-based science education (IBSE) needs to connect the task explicitly with the scientific context to ensure that the learning is meaningful. Rubtsov (2007) describes such a setting involving seven to 9 year-old children:

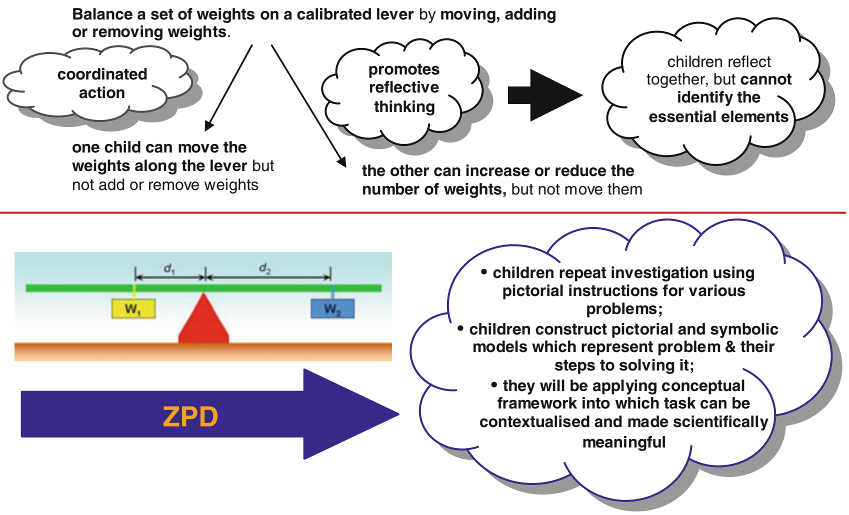

Fig. 4 ZPD to bridge IBSE with scientific conventions

> Two children must work together to balance a set of weights on a calibrated arm by moving, adding or removing weights. To solve this problem, they must take into account the relationship between each weight and its distance from the arm's centre of gravity. One participant is allowed to move the weights along the arm but not to add or remove weights; the other may increase or reduce the number of weights, but not move them. This division of activities, therefore, requires the two participants to work together, coordinating their activities in order to solve the task successfully. As the children move to the next problem, they switch roles. (p. 10)

Rubtsov (2007) cautions that such activities, while promoting reflective thinking, do *not* guarantee that each child will be able to identify the essential elements of the task. He suggests that to increase the effectiveness of the activity, children should be provided with *pictorial and symbolic models* to represent the problems they are solving and the steps they use to solve them. Hence they will be applying a conceptual framework into which their activity can be made scientifically meaningful. The pictorial and symbolic models, together with the discussion generated between learners as they complete the task, will become more meaningful to the children (and more so again with continued use with new, similar activities) (see Fig. 4).

This type of work will help to promote thinking and stimulate children to reflect and explain in order to understand how their experiences and their context-bound knowledge fit into a larger scientific system (Howe 1996). The teacher is essential here to guide the work and provide the conceptual framework. Howe argues that a contrasting, Piagetian approach would prefer that the children worked on their activity without teacher intervention. Howe maintained that:

> decontextualized tasks, chosen to represent a process but unrelated to children's everyday knowledge or interests, would not have a place in a science curriculum informed by a Vygotskian perspective. (p. 46)

Bereiter (1994) argued that school science exists predominantly in a context of mere learning, and that we should aim to move it towards one that constitutes knowledge building. He suggested that this situation could be achieved by activities aimed at collaborative creation in the classroom. Knowledge-building also requires that students use the scientific 'tools', including signs and symbols, so that their ideas can translate easily into scientific contexts.

Creating ZPDs to Enhance Science Communication in the Primary Classroom

Language is crucial to the development of scientific concepts. Scientific concepts have been developed by communicating, chiefly through language, ways to explain and manipulate the world around us. Of necessity, a scientific language has developed alongside such concepts, which communicates the ideas more efficiently. Thus learners need this language both to learn and to use scientific concepts. The language of scientific concepts is non-intuitive, and sometimes assigns scientific meanings to words used commonly in everyday speech (for example: force, energy). Learners ascribing the everyday context to these words are frequently described as having 'misconceptions' whereas, more likely, it is the case that the scientific use of the term has not been made explicit and the learner is expected to make a 'quantum leap' by using words differently in science without such differences being emphasised to them. Learners' contradictory statements about the world are not 'misconceptions'; they result from the lack of a scientific conceptual system in which to situate their ideas in their everyday concepts (Gredler and Clayton-Shields 2008).

Too much science learning in school and undergraduate science classes is aimed at individuals without engaging the importance of generating a shared language in the classroom to which all can contribute. Learners who are given opportunities to talk through their understanding of scientific learning and ideas, by group work and/or presentation, can be prompted in the use of scientifically appropriate language in the context of their own words. Teachers can listen out for and learn which terms are problematic and discuss ways of using such terms that are more meaningful for the learners. For example, in my observation of a pre-service teacher's lesson on the particulate nature of matter, 'Paul' was walking around the class checking children's work and asked an 11-year-old girl at the back of the class, close to where I (his supervisor) was sitting, which of gases, liquids or solids had the most energy. She answered 'solids'. Paul asked why she thought solids and she laughed, saying that it was because they were the strongest, "of course"! Paul tried to explain to her that the particles in the solid didn't move much, whereas those in the gas moved really fast, so they had more energy. However, she wasn't convinced—she raised her eyebrows and Paul moved on to another group. No 'bridge' was being made for the child's everyday linkage of strength to energy to particles in her experience to the scientific consideration of particle energy as totally separate from strength.

An example of a bridging activity that is designed to aid children in developing their own theories about phenomena using close observation is described by Murphy et al. (2013). Children (aged seven to eight) were introduced to the phenomenon of miscibility via a teacher demonstration of pouring syrup, then oil and then water into a glass jar. They observed that the water formed a layer between the syrup and oil, a phenomenon that they might not have expected. They then *repeated* the experiment in groups a few times (to introduce them to scientific replication) to observe very closely and see if they can come up with an explanation, based on their observations, for water displacing the oil. Following the experiment, children *presented* their theories to explain the phenomenon, using diagrams, writing and, if appropriate, presentation tools. This aspect constituted the ZPD created by the teacher to enable the children to work as scientists in this activity. An extract from one of the children's group presentations to explain the reason why water formed a layer between syrup and oil was:

> …the cooking oil is at the top and the liquid … there was bubbles in the cooking oil and it is free, like, it can move around and then it, amm, lifted up and then the water went underneath it. [8 year old]

This explanation prompted the researcher to go home and check for air bubbles in the oil—it was exactly as the child had described! This level of close observation and generating explanation consistent with the observations is rare, even at higher levels. Recently, Murphy (unpublished) carried out this same investigation with post-primary science student teachers, asking for explanations based solely on observation, not inference. They found the task extremely challenging and were absorbed totally in the activity. Indeed, they commented that this approach to science learning and teaching was one that they had almost never been exposed to. Primary school teachers can be encouraged to promote this method of teaching science, as opposed to asking children to learn facts. Such an approach would require assessment that focused on scientific reasoning, which might provide an excellent foundation for post-primary/tertiary level science learning about conceptual frameworks that have been developed by scientists to explain phenomena.

Other examples of activities of ZPD creation to promote dialogue and presentation came from giving children opportunities to express their ideas of how things might 'work' (Murphy et al. 2013). A 'black box' activity introduced by Hans Persson (now available on *YouTube*) called '*The Bucket*' was extended by teachers with a class of 6/7-year-old children. The teaching sequence started with a sorting toys activity followed by observation of the movement of a battery-powered toy car.

Children were invited to draw the inside of this car and to present their drawing to the class. The school principal overheard some children and created a ZPD for them to present at a higher level by offering his office for the presentations to a video camera. Each child sat in the principal's chair and spoke to the camera (see Fig. 5a). Their descriptions were recorded and transcribed. A typical one was:

> My name's … and I'm going to show you how this car works. The power of the pump goes into the batteries and makes more power in the batteries. And then it goes into the wheels. Then you push the button, and it goes zoom and fast. And then this here is the engine and these are the wires that are connected on to the engine… (boy, aged 6)

This description revealed the way that children were thinking, and bringing their experiences into the science classroom. The child above seemed to highlight his concept of 'power' in describing how the car moved. Amongst others, descriptions and pictures focused on the central function of cogs in turning wheels (see Fig. 5b) and on electricity. Video footage evidenced children's engagement with the task and their clear enjoyment of being given the opportunity to express their ideas in words as well as pictures.

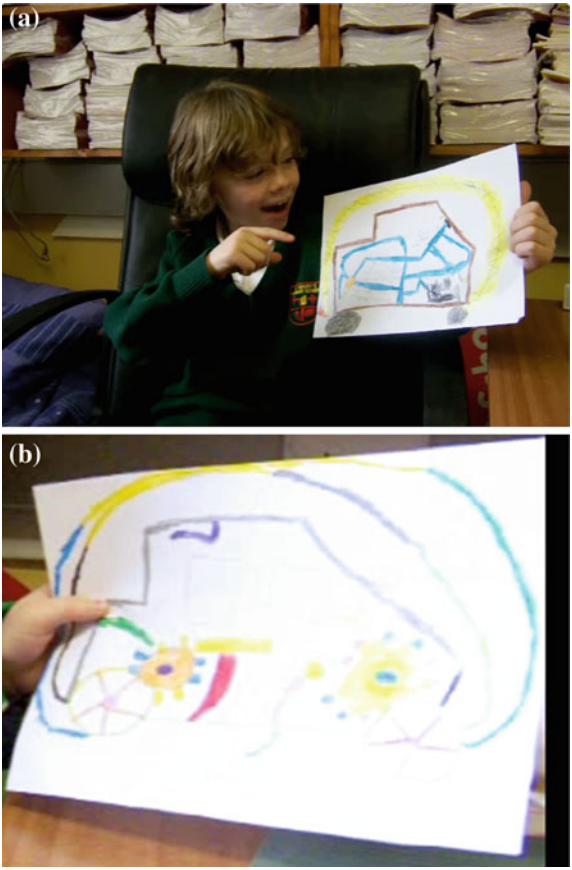

Fig. 5 **a** Child describing his drawing of the *inside* of a toy car. **b** Child's diagram of cogs *inside* the toy car

The teaching sequence continued with the children planning how they might build a car, using a selection of provided resources, such as cereal packets, plastic wheels, etc. They drew their plans and then built a prototype, which was tested and rebuilt accordingly. The final cars were raced and each child evaluated their own using two features they liked and one they wished they had included. Finally, children examined all the cars and selected their favourite feature from one of the designs.

These examples indicate a different approach to science learning and teaching that aims to promote and develop children's higher order thinking skills. ZPDs are specifically created to give children opportunities to act 'higher' than they would normally. The result is a higher cognitive level of expression and a desire to engage in science as a scientist. In other work (Murphy et al. 2010) children (8–9-year-olds) were invited to create designs of ancient animals using fossils. They were tasked to find out as much as they could using the internet and other resources during this activity, so that they would be carrying out this work in the same way that palaecologists reconstruct animals and ecosystems from the past. Questions children asked during this activity indicated a strong interest in knowing more and more as they learned. The awareness of how scientists worked in this field evidenced a contemporary view of the nature of science in which children described the work of scientists as systematic, but involving imagination and creativity. In her chapter (this volume) on questions learners ask, Seakins concluded that their questions are key to revealing much about their prior conceptions, interests, motivations and development, and could be used to a greater extent in science learning. Cowie and Khoo's chapter (this volume) discusses children's identity as scientists as a first step in developing scientific literacy.

Scientific Concept Development in Older Students

In post-primary schools the issues facing science teachers are different from those in primary or younger contexts. Whereas in the former, there are problems relating to teacher confidence to teach science and lack of support for teachers to promote IBSE, post-primary science is bedevilled with an outdated, crowded curriculum, assessment of factual knowledge, rigid schemes of learning to be followed by all departmental teachers in some schools and lack of time and support for IBSE. A consequence of these and other factors in post-primary school has led to disengagement of many students from science lessons. Scientific concept development in many schools follows the traditional approach (see Table 1), which is reinforced by the textbook and other resources.

Recently, I asked a group of 20 pre-service science teachers to carry out a quick survey of students in their classes (12–15-year-olds) to find out which was the most hated topic (science concept), and why. The most frequent response was *photosynthesis*; school students said they didn't need it, would never use it and that it was really boring to learn. Thinking of photosynthesis as a 'tool for understanding' as opposed to a concept to be learned made us reflect on how we might present it to students in such a way that they would be motivated to use it to explain something meaningful to them. Checking the 'textbook' introductions to photosynthesis revealed that the main questions for students to consider were the differences between plants and animals and how plants grow. Our next step was to think about a more meaningful context for teaching photosynthesis that might be of interest—perhaps the idea of what can plants do that animals can't? When the pre-service teachers tried this opening discussion in class, it led to greater student interest, especially when it transpired that plants could make food and oxygen, despite not having brains. Despite the fact that most students would have learnt this already, it was the *context* of that learning—a problem which meant something to them—that motivated them to think: *Well, how can they do that?*

Collaborative investigation of this problem, in which different student groups tackled different sub-questions, led to much more engaged and satisfied responses from students, particularly in tackling more difficult questions such as how much photosynthesis is needed to sustain the growing human population, which currently stands at more than seven billion and different estimates project it will reach 10 billion between 2083 and 2100. Pre-service teachers reported student-generated questions on deforestation and world food production and distribution arising from these lessons. This example provides an illustration of the idea that concepts are contextualised, and we can make such contexts meaningful in different ways (see also Reiss, this volume).

Students can also be invited to consider why they find certain scientific concepts *difficult*. Indeed, students can be introduced to ideas as to how we develop scientific concepts, as well as ways in which those concepts were created during the process of scientific investigation. Voelker (1975) suggested that some concepts could be acquired by students in a similar manner as they evolved within the scientific community (such as classificatory concepts of animals, plants, physical and chemical change) whereas others are almost impossible to learn in this way. The best that can be done with the latter group is to give students samples of activities that played a role in the development of the concept so that they can perceive some association of the roles of time, experience and human intellect in the formation of some of the more abstract, theoretical concepts, such as chemical bonding.

Some concepts can be acquired via teacher-mediated mechanisms, whereby teachers help students to visualise inputs that aided the evolution of the concept and show how it has developed in sophistication and application, for example: what, why and how consequences (good, bad; scientific and social) that have emanated from the publication of Darwin's theory of evolution have changed human behaviour, or how our understanding of the model of the structure of the atom has developed towards the potential impacts on society from nanoscience research. Van der Veer (1994) argued 20 years ago that students should be taught the tools of scientific thinking themselves. Such *thinking skills* are now a feature of school curricula in many countries.

My group of pre-service science teachers is currently working on a project to engage students by teaching concepts from the top-down, that is, by starting topics with challenges, beauty or wonders of science. For example, how life began; what is at the Earth's core; why the Moon is escaping the Earth; and how plants grow different shapes? For physics they are using a website developed for a public engagement project run by myself and science colleagues—http://www.dartofphysics.ie—that attracts people via 'adverts' and sustains the interest with an intense social media campaign and the website to generate a city-wide conversation about physics.

The work of Lancaster et al. and Rennie (this volume) also stress the link between 'real' science and school science as essential to future science learning. The role of the current teacher in making school science more engaging is considered by Loughran and Smith (this volume).

Summary and Conclusion: Revisioning Concepts in Science Learning and Teaching

This chapter has described the move from an individualistic model of a science learner and their learning to one that relies on social interaction, which is culturally dependent. For example, young children are taught to eat food with chopsticks in many Asian cultures, but with knives and forks in other cultures. Similarly, many Chinese students are taught from a Confucian perspective that the key to learning is *effort*, while little attention is paid to the idea of 'ability'. In most Western cultures, however, learning is frequently differentiated to address the learner's specific ability and 'learning style'.

In terms of learning and teaching scientific concepts, there are many differences between the traditional approach, which is individually-centered, and the socio-cultural approach, which has been addressed in this chapter. In Table 1 I have summarised these differences to provide guiding thoughts for teachers, learners, researchers, curriculum developers and other stakeholders in science education as ways to reconceptualise scientific concepts in science learning and teaching to make it more pleasurable, challenging, and, in the long run, more effective.

In conclusion, the work in this chapter provides a theoretical and practical exploration of scientific concept development. The aim is to provoke discussion and interest in looking at traditional science learning a bit differently. If we, as teachers, look at scientific concepts more critically as tools for science teaching (for example, as in the photosynthesis and http://www.dartofphysics.ie examples described above) we can make science lessons more engaging for ourselves and our students. We need also to change our learning environment so that students are engaged more actively in their science learning by promoting dialogue, student presentations, challenges and games. The move towards more collaborative and cooperative learning strategies in which students are encouraged and facilitated to repeat experiments as required mimics more closely the science world that they may wish to enter. Essentially, if we try to move from teaching the curriculum towards teaching students by engaging their interests and relating that work to the curriculum, we may significantly improve their scientific concept development.

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