OPINION PIECE

Concepts and conceptual understanding: what are we talking about?

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Abstract

The words concept and conceptual understanding are two words used frequently by physics educators, yet there is no satisfactory definition of either in the literature. In this article I discuss my own ideas of what these phrases imply for the practice of physics and physics education. I suggest that the word 'conceptual' is commonly used to imply qualitative reasoning. Although this seems to involve the use of simple relationships, this kind of reasoning is actually far from simple. It requires the coordination of seemingly disparate areas of knowledge and I argue that it is not always easy to distinguish between a misconception, or a false concept, and a failure to reason correctly.

Keywords: concepts, conceptual understanding, physics, misconception, modelling, reasoning

When I first became interested in physics education research, around 2002, I wondered to what extent the findings applied to the UK. This was, after all, a movement that originated in the USA, where the educational system is very different. Were the results as universal as the literature claimed or were they dependent to some extent on the educational system? This question seems to have been answered quite effectively within the last couple of years. Although never published, staff at the Institute of Physics interviewing graduates from across the UK for Teacher Scholarships have observed the same sort of conceptual difficulties shown by students in the US. I am not entirely surprised. I have been using the Force Concept Inventory for the past six years or so and have direct evidence that students entering my own

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department held at least some of the common misconceptions identified by physics education researchers over a number of years.

The idea that students hold misconceptions that are persistent and resistant to change has exerted a powerful influence over much of science education research. Misconceptions have been variously labelled as alternative conceptions, naïve conceptions or pre-conceptions, especially if they relate to mechanics, because it is well established that many such non-scientific ideas are developed in childhood as we make sense of the world. However, much of the literature seems to portray the idea that conceptions are either naïve or correct. This stark dichotomy would seem to be at odds with what many in higher education would consider to be a normal picture: that students can, and do, form incorrect associations and develop incorrect ideas. These are undoubtedly misconceptions in as much as students have misconceived the ideas taught to them, but they are formed as a direct consequence of the instruction received.

Misconceptions research has led directly to an educational agenda on conceptual change dominated by the idea that misconceptions should be replaced by correct conceptions. Much of misconceptions research is therefore about identifying more and more misconceptions so that we can design effective replacement strategies. One such strategy revolves around cognitive conflict: the idea that we induce some kind of conflict between what students think and what the expert knows and thinks so that students will give up their misconceptions in favour of the expert view. Smith and Rochelle (Smith *et al.* 1993), along with Andrea di Sessa, a psychologist in the USA whose ideas have been very influential among the physics education community, have called this view into question. They argue that not only does it effectively devalue students' ideas, as we must necessarily adopt the stance that we, as experts, are right and they, as students, are wrong, but it is also incompatible with the constructivist view of learning as a gradual process of constructing knowledge in which competing ideas often sit side by side. It is not surprising then that there are some who believe the term 'misconception' to be inappropriate and advocate that we should move away from this notion.

It is nearly 20 years since Smith's paper was published, but the views he cautions against are still prevalent. Part of the difficulty, it would appear, is the lack of satisfactory definitions in the literature. Whilst misconceptions provide something very definite to focus on, there is no accepted idea of what is meant by conceptual understanding or even a concept. Although both terms are widely used in the literature, there is a looseness about them that makes it difficult to place misconceptions and the research around them on a theoretical footing. Perhaps it is for this reason that Lillian McDermott (2001) preferred the term 'functional understanding', which she defined as connoting the ability to apply knowledge in contexts other than that in which it was attained. This probably comes closest to what most people would understand by conceptual understanding. It is common to find students being able to tell us this or that correctly and with confidence but unable to apply that knowledge and if knowledge cannot be applied to what extent is it really understood?

There is a considerable body of work on concepts in the literature, but it lies firmly within either the psychological or philosophical traditions. I have been deeply impressed by Nancy Nerssessian's work on creating scientific concepts through model-based reasoning (Nersessian 2008), but her description of a concept as a category didn't resonate with me. It was not until I read Edouard Machery's book, *Doing Without Concepts* (Machery 2009), that I realised that this is essentially the standard view of concepts. From a philosophical perspective the notion of concept-as-category makes sense. If we want to know whether something is a bird or not, to take an example, we have to have a clear idea of what it means to be a bird and one way of doing this is to create a category. However, I am not sure that it makes sense to do the same with physics concepts like force, acceleration, velocity, atom or electron. For the last in particular, how we think about it will depend on the situation. Sometimes it will seem like a point particle, at other times like a wave packet and at other times something else. Does that mean we have one concept that embraces all these possibilities or do we have multiple conceptions and choose one to suit the circumstances?

Is it important to be able to define what we mean by a concept in physics? I believe so for two reasons. First, if we don't know what a concept is, how can we be sure that the programme of replacing misconceptions by correct concepts is a sensible approach? Secondly, language is important as it reflects our thinking. What strikes me strongly about concepts and conceptual understanding is that common usage by physicists, even within the educational literature, seems to imply something different from the formal ideas of concepts as categories. The word 'conceptual' in physics usually implies a qualitative, as opposed to mathematical, approach, but qualitative reasoning does not always feature strongly within accounts of conceptual understanding.

To some extent di Sessa's proposal of a coordination class as a concept (di Sessa, 1998) addresses these issues. The coordination class is not an elegant construction: the name suggests something from object-oriented programming and with phrases like 'input' and 'read out', it looks like something a programmer would come up with. That aside, the name is intended to reflect the idea that to apply a concept it is necessary to coordinate several other items of related knowledge. Coordination in this sense does involve qualitative reasoning, but as di Sessa himself acknowledged, his proposal looks more like a model of understanding than a concept.

This idea of coordination does lead to a crucial insight, however: a concept is usually tested within some kind of context and this must inevitably require knowledge of other concepts. Does it make sense, therefore, to think about understanding of a concept in isolation? Is conceptual understanding context-dependent? My own researches on the Force Concept Inventory (FCI) have shown that students who appear to understand a concept in one situation can fail to apply the same reasoning in another, even within the same test. For a number of years now I have asked students at the start of the academic year to complete the FCI and during the last three years I have also asked additional questions to gain some insight into some of their responses. Last year I asked for a statement of Newton's three laws of motion and quite a number expressed the Third Law in terms of the force of an object A acting on an object B being equal and opposite to the force of B on A. Bearing in mind that students had done very little physics since finishing their A-levels some three or four months earlier, this could be considered to be fairly firm knowledge. Yet, when presented with a problem of a car pushing on a truck, which would seem to be a good example of an object A acting on B, many of these same students chose to apply Newton's Second Law rather than the Third. There was a clear association in this and other answers of net force with acceleration, but on a problem in which a box being pushed along a floor at constant speed is subjected to an increased force, and which should accelerate in consequence, the majority rejected the Second Law answer in favour of something unphysical, namely that the box should reach a constant speed at some point.

As part of the same test I asked the students to state explicitly what happened to the resistive force in this question and some of them correctly identified that it remains constant. After sifting through the responses I was left with a small number of students who could apply the Second Law in a number of situations and had all the necessary knowledge to recognise that a net force must exist in the direction of motion of the box, but who nonetheless thought the box would reach a constant speed. There is no discernible misconception at work here. It seems instead that some intuitive response has been invoked that prevented reasoning about the problem. As a test of understanding this question tells us only that students are not applying Newtonian principles, but had I not probed deeper into the answers I would have concluded erroneously that there is something about the Second Law or friction that these students do not understand.

This raises a more general question: when we ask students solve problems or answer questions designed to test understanding, what exactly are we assessing? Undoubtedly students will have false conceptions, whether naïve or otherwise, and sometimes these will underlie an incorrect solution, but in so far as such questions involve reasoning, which also involves coordinating disparate elements of knowledge, how do we know that we are not observing a failure to reason correctly? The short answer is that we do not, but it raises the question in my mind as to whether we should be trying to teach our students how to think conceptually as much as teach them physics.

Nersessian has put forward the idea that concepts are created through the process of iconic, analogic modelling, or model-based reasoning. I came across an example of this a couple of years ago. It was an interview presented by Scherr & Wittman (2002) with 'Sarah', who was described as an advanced physics student, discussing electrical conduction. A transcript of the full interview was available but unfortunately seems to have been deleted as the institutional website was updated. Nevertheless, a substantial proportion of the interview has been published for those who are interested (Wittmann & Scherr, 2002).

This interview attracted my attention because the interviewee, Sarah, develops a misconception about electrical conduction in metals. As described above, this is not the kind of misconception normally discussed within the physics education literature. Although the concept Sarah develops is incorrect it is a concept nonetheless and what we are seeing, in fact, is the creation of concepts essentially as described by Nersessian. The fact that it is an incorrect concept allows us to see the direct link between the final concept and her lack of knowledge, which extends to several aspects of the basic physics. She refers in places to an inductor when she clearly means an insulator, and she seems to have no understanding of the metallic bond.

In consequence Sarah struggles to explain why a metal behaves differently from an insulator, like

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polystyrene, when connected to a power supply. After some prompting and discussion, she focuses on what happens to the electrons inside the material. She has what seems to be a very strong notion that electrons within the metal are tightly bound to atoms and require energy to be released. When asked about the current flowing in two identical wires at different temperatures, Sarah settles on the notion that at higher temperatures there will be more energy in the system and concludes that current in a metal will increase with temperature because "more electrons can be torn away". Having arrived at this conclusion, Sarah thinks about it a little and then re-affirms her view in what seems to her to be a moment of revelation: "I didn't know why I didn't get the connection between the higher energy and the electrons being freed, but that's what I'm going with". Sarah has now developed a misconception about the nature of current flow in metals; current increases with increasing temperature.

Sarah seems to have been led to this misconception by her lack of basic knowledge, not only about electronic conduction in solids, but also, it seems, about solids in general. Both of the ideas she invokes, namely that electrons are bound to atoms and that the effect of a high temperature is to cause more electrons to be freed from these atoms, might apply in other circumstances but not to the situation under discussion. Thus, reasoning from insecure knowledge, she has to come up with a plausible reason as to why electrons in the metal should be free to move. Upon realising that free electrons are needed, she could have questioned her own assumption that electrons are bound, but she seems to have had no doubts about this. Consequently she develops an incorrect view of electrical conduction in metals which seems to be reinforced upon reflection. Even though she refers elsewhere in the interview to vibrating "structures", apparently meaning atoms, she appears to have no knowledge of phonons and their role in resistance, or, if she does, it doesn't feature in the interview.

What stands out to me is that the chain of reasoning is entirely qualitative. Sarah uses simple relationships, such as electrons being tightly bound to atoms or that the number of bound electrons decreases with temperature, to develop a model of electrical conduction in which electrons are torn away from their parent atoms. By model, I mean here not just a representation, which of course all models are, but also an explanatory mechanism. That her model is incorrect is not a consequence of the simplicity of her description, as she could just have easily described the relationship between temperature and the number of phonons or the presence of phonons and scattering to arrive at the correct conclusion that current decreases with increasing temperature. Her conclusion is incorrect for two reasons: first, those relationships she uses are incorrect and, secondly, there are others that she should have used but didn't, such as the relationship between phonons and resistance.

There is good reason to suppose that the kind of mental model that Sarah has created should be simple. It might be a gross simplification of what is undoubtedly a complex psychological construction to think of working memory only in terms of a limited capacity system, but it is well documented that the brain can only hold and operate on a limited number of separate facts or ideas (Glaser 1992). Experts can seem to hold more, as judged by simple recall tasks, but in fact associations between the elements in working memory and deep knowledge structures in long term memory are being triggered, thereby giving the impression that more things are being recalled. It is possible, quite likely even, that experts will use simple relationships when constructing qualitative arguments, as that is all the working memory will allow without some form of external representation.

There are, of course, more detailed aspects to these relationships, such as their mathematical expression. This kind of detail is certainly needed when solving problems or constructing a detailed model, but arguably it is not needed at the qualitative, or conceptual, level at which Sarah is operating as it would represent an extra load on the working memory. It seems to me, therefore, that these qualitative relationships are ideal candidates for concepts in physics. They correspond to the every-day use of the term and would appear to have a psychological validity.

If Nersessian is correct about model-based reasoning, and I believe she is, then students could be engaged in the process of constructing and consolidating concepts whenever they think about the physics they have been taught. Inevitably, as with Sarah, some of those concepts will be incorrect. In this sense conceptual understanding could be considered to be a fluid state that is constantly evolving, but testing that understanding is by no means straight forward. I have shown that what students might say about concepts in isolation can differ from how they use them. To use di Sessa's terminology, knowledge has to be coordinated and, depending on the context, the deeper structure of the concepts, or relationships, might also need to be invoked. These are two distinct processes, but they are both important and together they suggest an educational agenda in which process is just as important as content. By all means focus on misconceptions where we can identify them, but we need to teach students to reason qualitatively as well as quantitatively and, above all, to evaluate their knowledge. I don't think we will ever stop students developing misconceptions, but if we can teach them how to recognise when their reasoning is inconsistent I would consider that a significant step forward.

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