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How students construct knowledge during their university years is important for their future careers where the ability to integrate, evaluate and apply scientific knowledge is required.

Epistemological beliefs and intellectual development in the physical sciences

Abstract

Much research has been documented on the stage of students' intellectual and epistemological development during their studies and upon course completion. To a large extent, the literature suggests that promoting students through the intellectual framework is a desirable feat. Indeed, students graduating from university at the more developed stages of intellectual and epistemological sophistication are better equipped to synthesise, evaluate, organise and cross reference knowledge into different domains.

In this review, modes of epistemological beliefs will be discussed as sources of valuable information to departments about the quality and nature of students' perceptions of learning and teaching. The results of recent research in epistemological and intellectual development will also be discussed; this perhaps being a mechanism to inform learning and teaching practices within the physical sciences.

Epistemological and Intellectual Development

Epistemology refers to the justification, nature, sources and evaluation of knowledge^{1, 2, 3}. It has been reported that epistemological and cognitive sophistication is positively related to skills such as critical thinking, self regulation⁴, ability to communicate ideas and to learn in collaboration⁵. Indeed, physical scientists may be viewed as professional epistemologists in that they use prior knowledge to generate knowledge through explicit and reliable methods. How students construct knowledge during their university years is important for their future careers where the ability to integrate, evaluate and apply scientific knowledge is required.

The investigation of students' perceptions of learning, teaching and epistemological beliefs in the sciences has been widely researched because of their influences on learning, goal orientation and use of cognitive strategies^{6, 7, 8}. This has been a relatively active area of research^{8, 9} and can be traced back to the original intellectual and developmental work of William Perry in 1968¹⁰. His theory offered an unfolding of students' views on development, learning, authority and the nature of knowledge as they progress through their university years. A scheme that conceptualised the development of higher cognitive skills was formed (Table 1), providing a specified hierarchal sequence of human experience from basic duality to identity, commitment and maturation (see also the work by Bhattacharyya¹¹). The intermediary stages are typified by dissonance where individuals encounter and recognise imperfections and fallibilities in 'authorities' (e.g. models, textbooks etc).

Perry argued that the most significant intellectual shifts occur during university, when students are confronted with and expected to reconcile multiple authoritative sources. Cognitively, students become active generators of their own knowledge and become socially aware of their commitments and identities.

Perry reported that few students enter university at the basic dualistic stage and in his study; he found that over 70% of students leave university having attained levels of commitment, exemplified by stages 7 and 8. Perry also suggested that individuals may depart from the main line of development by suspending, nullifying or even reversing the process of growth.

Table 1: Perry's scheme of intellectual development as applied to the learning situation

Stage	Description	The learning situation
1: Basic duality	The student views life in polar terms of right v wrong. The correct answers are known to Authority whose role is to mediate them. Knowledge and goodness are to be collected by hard work and obedience.	The student is a passive acceptor of factual, clear cut knowledge that is committed to memory and obtained solely from the lecturer. Exams are viewed entirely from a factual objective perspective.
2: Multiplicity pre-legitimate	Diversity of opinion is evident and the student accounts for this as poorly qualified Authorities. Students may even view this diversity as mere exercises where they are required to obtain the right Answers on their own.	
3: Multiplicity Subordinate	The student begins to accept diversity as legitimate since the limitations of duality are exposed. However, the standards required (e.g. for grading) are vague.	The student may sit in a trough of dissonance where the factual clear cut nature of knowledge, authority and responsibility is unclear. The student appreciates that the dualistic construct may not be absolute, and requires guidance from the lecturer for knowledge, assessment and grading.
4a: Multiplicity correlate or relativism subordinate	The student perceives that diversity of opinion and uncertainty to be legitimate "and raises it to the status of an unstructured epistemological realm of its own" where everyone has the right to their own opinion. This is now set over Authority's realm of right-wrong.	
4b: Multiplicity correlate or relativism subordinate	The student begins to discover contextual relativistic reasoning.	
5: Relativism correlate	The student views all knowledge and values as contextual and relativistic and completely dismisses the dualistic perspective.	Students are active constructors of knowledge and view themselves, peers and lecturers as legitimate sources of knowledge. The student enjoys debating in different contexts and views exams as opportunities to demonstrate skills, creativity and independent thought. Relativistic thinking becomes the norm and can confidently discriminate between facts and opinions.
6: Commitment foreseen	The student appreciates the relativistic world and needs to orientate himself towards some sort of commitment.	
7: Initial commitment	The student constructs an initial Commitment in some area.	
8: Orientation in implications of commitment	Implications of his commitment are evident and the student explores his realm of responsibility.	
9: Developing commitment	Through the initial affirmation of identity, commitment and responsibility, the student views life as an ongoing journey where multiple commitments and responsibilities are required.	

Recently, much emphasis is placed upon how university experiences affect students¹², and Perry's theory has remained the cornerstone and guiding framework of many research studies of student development, throughout their education and onwards throughout their careers.

Because of limitations in the original scheme, other similar theories^{13, 14, 15, 16} have since been reported and most are concerned with the development of individuals' beliefs ranging from the stance of black and white absolute thinking to a sophisticated, evolving and rationally evaluated viewpoint of the world.

Literature review

How students approach their physics learning has been reported to be related to their perceptions of knowledge and the nature of physics^{17, 18, 19, 20}. For example, May and Etkina¹⁸ have shown that through the use of students' submission of weekly reports, those students who showed higher conceptual gains were more likely to mention more developed epistemological learning activities, such as learning formulae with conceptual understanding with a lesser reliance on

authority. Nussbaum, Sinatra and Poliquin²¹ have reported that those students classified as evaluatists interacted with knowledge more critically and were better at solving physics problems than those students who were classified as multiplists. Multiplists were less critical of misconceptions and inconsistencies in relation to problems in air and gravity. Richter and Schmid⁴ showed that epistemological attitudes and beliefs affect self regulated learning. Hammer¹⁷ also reported that novices tend to solve problems by manipulating formulae where physics knowledge is organised by surface features as opposed to by physics principles.

Another study illustrated that student success in an introductory undergraduate physics course for naïve learners, is dependent upon student's cognitive understanding and on their epistemological beliefs of physics²². Their weekly interviews over 12 weeks looked at students developing conceptions of sound and wave motion. Although the sample size reported is small, an in depth analysis revealed that naïve first year physics undergraduates tend to use different models than experts for understanding sound and wave motion. Their interviews elucidated three 'types' of students:

Table 2: Example of an Osgood type questionnaire

It is good to work with other students because listening to their points of view, I can correct my ideas							I prefer not to work with other students because I might pick up some wrong ideas
I think lecturers should avoid teaching material that they know students will find difficult.							Lecturers should aim to provide challenges to students by introducing difficult topics.
All I have to do in science is to memorise what has been taught							Understanding science is the key to scientific study

1. Some students (without prior physics knowledge) believed that scientific knowledge is conceptual knowledge and developed most of their preinstructional conceptions into acceptable scientific conceptions. Their beliefs about physics knowledge enabled them to choose viable study methods where the physics that they learned in lectures was helpful for understanding the real world.
2. Some students (with prior physics knowledge) believed that physics knowledge is mathematical knowledge and did not develop their conceptions well. Their beliefs that physics problems were simply mathematical formulae and the physics they learned in lectures were not relevant to everyday experiences.
3. Some students viewed physics knowledge to be made up conceptual knowledge where the ultimate goal was to understand formulae to solve problems mathematically. However, no effort was placed on appreciating the conceptual content that was involved. They believed that learning in physics was totally unrelated to their everyday experiences because of the complicated words and meanings.

The progression in student thinking showed that conceptions developed from everyday conceptions to unclear scientific conceptions and finally to scientific conceptions. However, this illustrated that the extent of students' previous physics knowledge did not necessarily influence the development of their physics conceptions.

Although set at secondary school level, it has been reported that epistemological sophistication in physics can be a predictor of conceptual understanding in physics⁷. Stathopoulou and Vosniadou⁷ explored this relationship and all students who showed a deeper understanding of Newtonian dynamics were students with highly sophisticated beliefs. Interestingly, Liu and Tsai² examined differences between science and non-science majors on their epistemological views. Their results indicated that science majors have less sophisticated beliefs in the theory-laden and cultural aspects of science than non-science majors. They account for this by suggesting that science major students might have been longer involved in an epistemic environment that described scientific knowledge as being objective and universal.

In the Swedish context, Domert, Airey, Linder and Kung²³ analysed undergraduate and postgraduate students' epistemological beliefs in learning physics equations. They found that advanced physics students felt the need to understand the underlying physics concepts to be more important than those at the earlier stages of their studies. The authors suggest that physics students at the early stages of their learning should be encouraged to link equations to everyday life.

The study by Sins, Savelsbergh, van Joolingen and van Hout-Wolters⁸ explored the relation between students' epistemological understanding of models and modelling and of their cognitive processing (i.e. deep versus surface processing^{24, 25}) on a computer based physics task. They found (and expected) a positive correlation between students' level of epistemological understanding and their deep processing. This is similar to the work reported by Ozkal, Tekkaya, Cakiroglu and Sungar²⁶ in that students who believed that knowledge was tentative appeared to use learning strategies that resulted in deeper processing of information. In addition, Scherr and Hammer²⁷ argued that the concept of observing students' behaviours *in situ* in small group physics tutorials can be useful for determining student epistemologies. For instance, "A student may frame a physics problem as an opportunity for sense-making or as an occasion for rote use of formulas". They found that verbal and non-verbal displays reinforce each other and provided evidence for certain student behaviours that indicate a support for epistemological framing.

Tsai²⁸ discussed a constructivist internet-based learning environment for students and reported that more advanced graduate students require opportunities to negotiate ideas, reflect and explore epistemological issues. In addition, students with more internet experiences tended to prefer more features of the constructivist internet-based learning environments than those with less internet experiences. He believed that the internet based learning environment can be perceived as an epistemological tool (as opposed to a cognitive tool) where learners can "develop evaluative standards to judge the merits of information and knowledge, thus exploring some epistemological issues."

What the above studies tend to suggest is that a consideration of epistemological beliefs and attitudes is important in the physical sciences – both for educational practice and research.

Interventions

There is a general consensus in the literature that encouraging students through the intellectual and epistemological framework is a desirable aim of higher education^{29, 30}. Indeed, it is known that sophisticated epistemological beliefs exert a positive influence on students learning strategies and learning outcomes^{31, 32}.

In the chemistry laboratory:

Whilst not explicitly related to epistemological and intellectual development, the research of Kelly and Finlayson³³ has shown that a problem based learning approach in the chemistry laboratory is more conducive to learning and understanding chemistry when compared to a traditional approach. They researched students' attitudes to learning in a problem based laboratory (where the procedure is student generated) as opposed to the traditional expository laboratory. It may be argued that this technique would encourage intellectual growth, as reported by the case of MacKenzie, Johnstone and Brown³⁴ in the context of medical education. Their results showed that students undertaking the new problem based learning curriculum demonstrated a more critical, self directed approach to learning and argued that the same can be embedded within science curricula.

Scientific argumentation – web and individual text based:

Embedding skills of scientific argumentation³⁵ within an introductory physics course has been shown to encourage students to develop more scientific criteria in discussions, in addition to increasing success and conceptual understanding of physics problems²¹. The study was conducted on an online web environment (n=88 undergraduates); this being the vehicle for student discussions, in addition to documenting and coding responses for analysis. Both groups completed online questionnaires on the scientific disposition to argue and an epistemic belief survey and were equally divided into groups. The treatment group received additional online skills in scientific argumentation. The intervention was found to have positive effects in terms of the number of thought experiments, alternative views and qualities of scientific arguments. Although students' willingness to engage in argumentation can vary, the authors argue that it is an important part of the socially constructed nature of scientific enquiry.

The work conducted by Mason, Gava and Boldrin³⁶ with pupils in Italy, investigated two types of instructional texts in light, vision and colour: (1) an ordinary expository text whose function was to give new information and (2) a "refutational text that not only gave new, correct information but also explicitly stated and refuted alternative conceptions by

presenting the scientific conceptions as viable alternatives". They found that the refutational text facilitated students understanding of new concepts and situational interest.

Overall, epistemological beliefs and exposure to the criteria for sound scientific argument can affect learning of physics concepts – an increasingly important area since research has reported that students may complete physics courses without a proper conceptual understanding of physics³⁷.

Historical perspectives of chemistry:

Using written reports and classroom discussions, Niaz³⁸ has shown that when students are given the opportunity to reflect and debate various chemistry topics (such as the various models of the atom), understandings of the nature of science can be enhanced (see also the exploratory work of Ibrahim, Buffler and Luben²⁰). Niaz also concluded that the interaction among participants facilitated the progressive transitions in students' understandings of the nature of science.

Course type and environment:

Tolhurst³⁹ conducted a study to examine how epistemological beliefs may be affected by the implementation of a new course structure. It was found that students were more actively engaged in their learning and positive changes in epistemological beliefs were generated. In addition, students with sophisticated epistemological beliefs attained better results in the end of year examination. More recently, other work by Baily and Finkelstein^{40, 41} has demonstrated how students evolve in their thinking as they moved from classical physics to quantum physics. It was found that student perspectives change when making the transition between classical physics (realism, where all physical quantities within that system can be specified simultaneously) and quantum mechanics.

Summary

In order to inform learning and teaching practices, departments may wish to document and analyse students' epistemological and intellectual development during a degree course⁴² (or before and after an intervention). In turn, the results of such research might further influence the way departments support learning and teaching, and in particular for future student cohorts. Much of the research described above shows that when it comes to learning physical science concepts, student epistemologies matter. In designing effective learning environments, researchers suggest that it is important to develop and evaluate curricula that will facilitate the development of sophisticated epistemological beliefs⁷.

Appendix – Questionnaires

As the Perry scheme is relatively complicated, various simplifications^{15, 42, 43} have been offered, mainly as a means of simplifying measurement and presentation. Various attempts in the literature have been made to convert the epistemological framework into a questionnaire, some of which are listed below:

- (1) Example of an Osgood type questionnaire (Table 2)
- (2) Evaluation of Teaching, Higher Education Academy Physical Sciences Practice Guide⁴²
- (3) Views on the nature of science instrument⁴⁴
- (4) Student submission of weekly reports¹⁸
- (5) Views About Science Survey (VASS)⁴⁵

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