Exploring the Structure of Knowledge Organisation in Physics Learning

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Research on understanding various aspects of learning is multifaceted. Cognitive science research has contributed significantly towards the answering of the complex question of "how mind works". Understanding learning within the frame work of formal instruction has formed the central aim of educationists. Physics Education Research (PER) addresses the issues of domain specific learning. In this paper, we present the results of our research, which attempts to probe the mental organisation of knowledge structure using the now established methodology of PER. The use of abstract ideas coupled with the necessary use of tools of mathematics in learning of physics content appears to have resulted in learning difficulties, understanding of which is expected to throw light on several aspects of learning as well as general understanding of how people learn.

Keywords: Epistemy, Physics education research, Conceptual understanding, Knowledge organisation

Introduction

> *"The simple but difficult art of paying attention, copying accurately, following arguments, detecting an ambiguity or false inference, testing guesses by summoning up contrary instances, organising ones time and ones thought for study – all these arts…. cannot be taught in air but only through the difficulties of a defined subject; they cannot be taught in one course in one year, but must be acquired gradually in dozens of connections" - Jacques Barzun.*

The above quote in its simplest form attempts to summarize the general expectations of any learning process. Understanding 'how people learn' has been one of the most important aspects of research for a great number of researchers involving neuro-biologists, cognitive scientists, psychologists and more recently physicists (Huttenlocher & Dabholker, 1997; McDermott, 2001; Norman, 1980; Redish, 1994). Research results on understanding how people learn have tremendous implications in education, i.e., in the science of understanding the process of teaching and learning. No curricular recommendation, reform, or proposed structure has ever been made without some obeisance to the generic term "critical thinking" or one of its synonyms. Efforts are plenty in the recent years at every level of education that call for attention to the enhancement of thinking- reasoning capacities of the learners. However, the roadmap for the enhancement of thinking and reasoning capacities offers some degree of specificity and some operational definition of the concept with illustrations of what can be done in classroom instruction to achieve the enunciated goals. A perceivable enhancement of these skills may be achieved by a deeper understanding of the learning process (Bransford, Brown, Cocking, 1999; Mestre & Tougher, 1989; Thagard, 2005).

Teaching/learning is predominantly a communication which is the transfer of information. Communication by codes has the advantage that it makes the transfer of information fast and efficient. Communication by codes can work only if there are preset patterns. Understanding learning in the light of cognitive processes is interesting and complex. Cognitive science, models the mind as a pattern making system and hence mind is perceived to resort to communication by codes. Therefore, it must build a catalogue of patterns. The mind with its ability to create, store and recognise patterns handles information in its characteristic way. However, there exists a limitation inseparable from the advantages - particularly in restructuring patterns. In particular, the mind is good at establishing patterns but not at restructuring them. Restructuring is more of a deliberate process. It is from these inherent limitations that the lateral thinking idea of Edward De Bono (1973) is a promising remedy or alternative to overcome this limitation.

Though learning encompasses acquiring multifarious skills, in the context of this paper, the term learning is used for acquiring of those skills which form a part of formal education. Education in its simplest form has always been regarded as imparting content knowledge in the appropriate domain. However, recent trend have redefined the objective of education as the process of imparting skills that aid the enhancement of thinking-reasoning capacities of the learner.

As suggested by the quote above, content may at best be regarded as a tool for acquiring the specific skills necessary for learning – for, these skills are domain specific. For example, learning music requires strengthening of skills that are definitely different from that of learning wrestling. Learning of skills required for effectiveness in a domain forms a subset of a larger set of skills. In this context, it is important to identify the prerequisite skill set for a specific domain learning, for example learning of physics. Physics education research (PER) in the last three decades has evolved as a major research field in which research on various aspects of learning of physics is explored (Maloney, 1993; Redish, 1998; Zollman, 1995). This area of research has evolved with robust methodology and standard practices. To be able to understand and analyse the processes involved in the teaching/learning of physics, research requires the involvement of domain experts – i.e. physicists.

This brings us to the question of implications of the above cognitive model in the domain of physics learning. The notion that understanding of physics can be achieved by mere verbal inculcation seems to be a principal source of failure in understanding physics learning. Such an instructional method helps the student attain what is considered as the mark of a scientifically literate person rather than a competent person. There is increasing evidence that this process of instruction is not effective at cultivating the operative knowledge in any of the formal disciplines and teaching of science is not unique in this respect. In the initial years of PER, research results from cognitive sciences formed an important input. The breakthrough in cognitive studies in the past few decades has been to model what is happening in the mind in terms of inferred structures. Learning involves thinking in terms of mental patterns as students tend to organise their experience and observations into patterns or mental models. Results of PER have been interpreted in the light of existing cognitive theories. Presently, with its rigorous research methodologies, the PER results are useful inputs for understanding the "understanding" and are widely used to build theories of learning. Initial research in physics education was intended to be of use in physics teaching/learning. Identifying the preconceptions and misconceptions held by students formed an important aspect of PER. The research had a very strong intended application for improving instruction methodologies and curriculum development. More recent works address various aspects of understanding the content, development of new methods of teaching and also the general approach to the process of learning (Crouch & Mazur, 2000; Laws, 1996; Van Heuvelen, 1991).

This paper looks into the organizational aspects of knowledge structure and the establishment of logical connectivity, especially in the context of physics learning. The objective of physics instruction is to develop a certain degree of competency in learning physics and also to identify the learning difficulties encountered by classroom instruction and/or textual material. Probing into students' learning difficulties in the domain of physics learning will generate pointers to help evolve methodologies to acquire the required competency.

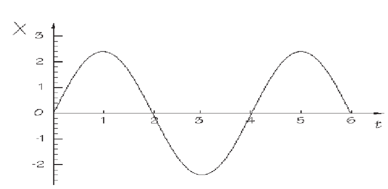
Methodology

Analysis of responses to questions designed to examine specific aspects of student's ideas about chosen topics has been a widely used technique in PER. The questions may be in the open ended form or in the multiple choice format (Rosengrant, Van Heuvelen, Etkina, 2009). Statistical analysis of the data then brings out patterns that mirror a student's ideas (Ding & Beichner, 2009). This requires a sample size large enough to make statistical analysis relevant. Another equally accepted methodology is to conduct detailed interviews on a smaller number of students. The responses of students are recorded and analysed to get an insight into their learning processes (Mason & Singh, 2010). We have combined both the approaches. In our study, the responses to multiple choice questions (MCQ) have been primarily used as pointers for the development of the interview protocol. The interview is designed to progress with scaffoldings in which the weakest scaffolding is presented first. The details of the scaffolding and the considerations that go in its design are explained later in the context of the problem chosen for the study. The nature of scaffolding and the stage in which the student uses it reveal a great deal about their knowledge structure.

In the first stage of this research, we administered the following question (along with other twenty one questions) to a large number (about three hundred) of undergraduate students. The students were from an undergraduate program where physics is one of the subjects of study. All the students interviewed were in the age group of nineteen to twenty one years.

The physical situation enunciated in the question chosen is presented in an unfamiliar context. The nature of x *versus* t behaviour in simple harmonic motion (SHM) is "familiar" to students, whereas the problem situation is not. Learning should enable a student to not only use what is explicitly taught (either by instruction or by textual input) but also enable the student to apply it in unfamiliar and altered contexts. Perceiving the latter as a major difficulty in learning, we have selected the following question for a more detailed analysis. It is important to note that the objective of this study is not to explore student's understanding of simple harmonic motion. We intend to understand the student's knowledge organization of various physics concepts. This can be achieved if the student is presented with a physical situation of known physics concept in an altered physical context.

Question: The displacement (x) versus time (t) graph of a particle executing SHM is as given below.



Graph of momentum versus displacement is a

A. Straight line

B. Parabola

C. Circle

D. Ellipse

Students who responded to this physics question had undergone formal instruction on various necessary concepts like simple harmonic motion, graphical representation of physical quantity etc. It is important to note that the question is in the multiple choice format and the incorrect responses indicate the existence of difficulties but cannot expose the actual reasons for the learning difficulties or the nature of the difficulties. The response of students to the question is indicated below. Option D is the correct option.

The responses of students have been analysed and used to identify pointers to develop the interview protocol. Eleven students were interviewed and the interviews were conducted in an open ended manner without a constraint on time.

Design of Interview Protocols

Development of interview protocols with specific objectives is a very important part of our research. The progression of the interview is such that the weakest scaffolding is used in the beginning and the strongest scaffolding is presented at the end. For example, a student solving the problem may attempt to recall the relevant equation as a first step rather than attempt to recall the physical principle. Hence presenting the equation is the strong scaffolding whereas the physical principle is the weak scaffolding. The nature of the scaffoldings and their sequencing is decided based on detailed analysis of the MCQ responses. A few validation interviews were conducted before the actual data interview and the scaffoldings were fine tuned and sequenced accordingly.

When presented with a multiple choice question, a student may use any one of the following methods to choose an option. The student may choose an option randomly-without reasoning scientifically, may choose an option because of correct or incorrect physics intuition or may choose an option based on firm scientific reasoning. It is the design of interview protocol which should be capable of identifying the method chosen for the choice of an option.

The question presented to the interviewee was slightly modified from its MCQ counterpart. The question is as follows.

Question: A particle is executing SHM. Graph of momentum versus displacement is

A. Straight line

B. Parabola

C. Circle

D. Ellipse

E. Sinusoidal

The important considerations for the design of the interview protocol are presented below.

— The question has been altered from the one given for the MCQ test. The graphical representation of the *x versus t* plot has been deliberately omitted. The objective is to see which of the representation of SHM i.e., mathematical or graphical is easily understood by the student and hence used with ease.

— Students using graphical representation were asked to use the mathematical representation and vice versa.

— Students who did neither were presented with the scaffolding that the plot of SHM is sinusoidal in nature or that *x versus t* graph is sinusoidal.

— Students who wrote the equation of SHM were asked to identify the physical quantities associated with the symbols. Physics learning involves association of physical quantities with symbols, more often than not, with a great deal of degeneracy. For example, think of all the physical quantities represented by ‘T, *s* , n’!

— Even after being equipped with the equation, if there existed an inability to progress, we presented the scaffolding that velocity is the derivative of displacement, and prompted them with the definition of momentum.

— The next step was to test ability for mathematical manipulation. If unable to progress, they were presented with the next scaffolding i.e., the equation of an ellipse.

— The next step was to see the ability to use multiple representations. Students were asked to represent each of the choices using both mathematical and graphical representations.

— Learning physics involves concepts like vectors whose abstract nature belies commonsensical understanding. The form of use of these ideas follows specific rules. For example, a vector cannot be added to a scalar. Similarly, a vector cannot have mathematical equality with a scalar etc. We test this skill by posing the question about the vector or scalar nature of quantities in the equation $x = A \sin \varpi t$.

— The students were then asked to give an example of the physical situation represented by $x = A \sin \varpi t$.

Interview Results and Discussions

Eleven students were interviewed for this question. In the initial response, six students chose option (A) and five chose option (E) and only one chose option (D). As mentioned earlier, student may choose an option randomly without scientific reasoning, may choose an option because of correct/incorrect physics intuition, or may choose an option based on firm scientific reasoning.

Our question is amenable for an answer by use of physics intuition. An expert mostly uses these skills, whereas a novice may not do so readily. In simple harmonic motion, the velocity is maximum and hence kinetic energy is maximum in the equilibrium position. The velocity and hence kinetic energy is zero at extreme positions. Hence, a graphical representation of these features suggests the answer to be either option (C) or (D). However, only one student approached the problem by this route.

Six students expressed SHM mathematically, two students did it graphically and three did neither. Students appear to believe that learning physics is a matter of acquiring new knowledge in the form of principles, laws and equations and learning is a process of remembering or storing equations (especially in the context of physics). Since our instruction places emphasis on the role/need of mathematics in physics, equations are learnt more seriously – this can happen only through rote learning. The conventional mode of evaluation also requires recalling of equations heavily. Hence, students tend to write mathematical equations from rote memory readily. Graphical representation or translating a mathematical equation to graphical representation appears to be complex for a student since rote learning is of not much use here. Of the eight students who expressed either graphically or mathematically, only five students could express using both representations effectively. For those who did neither, the scaffolding that *x versus t* is sinusoidal was useful.

Of the 11 students, only 4 of them could identify the symbols correctly. Rest of them had some ambiguity about ù. To a majority of students, *x* meant displacement whereas *x* is the instantaneous displacement. A mathematical equation is merely a relation between the various physical quantities. However, students can recall an equation without knowing the meaning of the representative symbols as their knowledge is organised by surface features rather than by underlying physical principles. What makes the association of symbols to physical quantities difficult is the inevitable degeneracy in the use of symbols – the same symbol may be used to represent several physical quantities.

For those who did not progress with the solution, what was useful was the scaffolding for velocity. Nine of them attempted to arrive at an expression for velocity but only seven of them did it successfully. Out of the eleven, five of them used the scaffolding for momentum. During teaching of simple harmonic motion, an explicit instruction exists about the nature of behaviour of position with time. Definitional aspects of physical quantities like momentum and velocity are learnt in some other context. Our question requires an integration of both these information. It appears that the knowledge students acquire is a collection of isolated pieces. One either knows a piece or does not know.

This problem also requires the use of mathematical manipulation skills. None of the students proceeded to solve the problem even after presenting the equation in terms of momentum. Mathematical manipulation is an essential component of physics learning. Upon presenting the scaffolding of the equation of an ellipse, only two students could completely solve equation for momentum and recognise that momentum versus displacement graph is an ellipse. Inadequate skills in mathematical manipulation were definitely a hindrance for the rest of the students. Failure of students to proceed further with or without scaffolding indicates that students show a reproductive view in learning rather than a reconstructive view. As far as the writing of mathematical equations for the choices in the question, seven students could write the equations whereas four of them could represent it graphically which again reinforces the idea that recalling of mathematical equations is easier.

For testing higher order cognitive skills, when asked if displacement is a vector or scalar, seven answered it as a vector; three answered it as scalar while one student was not sure whether it was a scalar or vector. In the equation $x=A \sin \varpi\ t$, if *x* is known to be a vector, most of the students associated vector property erroneously to the amplitude. While dealing with vectors, there are certain operational features such as a vector nature which has to be balanced in an equation. If a student is aware of this, there is no reason to recall erroneously. If *x* on the left is a vector, the right hand side is also a vector. This brings us to the important aspect of instruction - it is the process which is more relevant in instruction rather that the details of the content. Seven students did not recall the physical situation represented by the equation $x=A \sin \varpi\ t$. Four students recognised the equation as that of oscillatory motion of the simple pendulum. Students often prefer an oscillating simple pendulum as the most popular example of an object undergoing SHM. However, the correct answer to the representing equation is an example of one dimensional SHM.

The problem selected for our study requires that students use well understood simple physics ideas but in altered situations. The detailed interview analysis exposes the nature of weak interconnections in students' internal representations. The intuitive knowledge acquired by the students appears to be fragmented and contextual; learning is perceived as receiving knowledge from authority. Learning may not be of use to consciously distinguish between declarative and operative knowledge. Existing instructional methodologies in physics rely heavily on rigour of content. Despite sincere efforts at teaching and fair competence in content, teachers are often faced with situations that display deficient learning outcomes. In the present scenario, a majority of physics teachers are not well acquainted with various inputs about the understanding of 'learning'. The restructuring and reorganisation of existing mental patterns among students necessary for effective learning is expected to occur without any deliberate attempt. If attention is also paid to the 'process' and not only to 'content', instruction would become more effective. An understanding of the 'processes' makes a call for the kind of research discussed in this paper.

Conclusion

Physics education research aims at understanding domain specific learning difficulties and evolving remedial methods. The primary goal of this area of research is to make physics learning effective. However, an insight into the microstructure of physics learning can have interesting ramifications in the understanding of "understanding". The paper discusses the methodology and analysis of a technique to probe student knowledge structure. The results of our analysis confirm weak interconnections in student knowledge structure and support the relevance of understanding of processes in addition to the content.

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