

# [O26] Physics education research and UK physics; tensions and possible remedies

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## ABSTRACT

Physics education research (PER) is a systematic activity aimed at identifying weaknesses in students' understanding of physics in order to develop instructional methods to overcome them. These methods stress understanding over content, which inevitably leads to reservations about applying the findings in UK universities where physics is taught within a dedicated and concentrated programme with a prescribed minimum core content. In this paper the findings of PER are shown to be consistent with established cognitive theory and models of thinking. Thus the outcomes of PER can be generalised and extended to other areas of the physics curriculum and a cognitive model for teaching physics is established. This model allows teaching for understanding without reducing too much the course content. In particular, the educational value of small-group work for instruction in problem solving skills is emphasized.

## INTRODUCTION

The view has arisen that conventional teaching methods serve only the minority in today's higher education system (1). Biggs in particular has put forward the view that constructive alignment of teaching should lead to improved learning. Constructive alignment is based on the principle that it is what the student does that determines what is learnt rather than what the teacher does, so by aligning teaching methods to student learning

activities learning can be enhanced. This view applies to higher education in general but remarkably it coincides with the results of physics education research (PER) in the USA. Unlike much of education research, which is concerned with educational theory and cognitive psychology, PER is regarded as a research discipline which sets out to identify misconceptions and find instructional methods to overcome them. In the words of one of its leading exponents (2),

'Physics education research differs from traditional education research in that the emphasis is not on educational theory or methodology in the general sense, but rather on student understanding of physics. Such research requires an in-depth knowledge of the subject as well as access to students, which means that it can usually only be carried out by physicists working in physics departments. The findings form a rich resource that provides insights into how students learn physics. When teachers apply this information and document the results for others to use, cumulative improvement in instruction is possible ...Our research indicates that although students vary in the way they learn best, learning is not as idiosyncratic as is often assumed. Students at the same level of study respond in a remarkably similar way to certain kinds of questions, both before and after standard instruction via lectures, textbooks and lab classes.'

PER identifies the following difficulties with the standard 'chalk and talk' method of course delivery (3,4).

- Facility in solving standard quantitative problems is not an adequate criterion for functional understanding
- Connections among concepts, formal representations, and the real world are often lacking after traditional instruction
- Certain conceptual difficulties are not overcome by traditional instruction and advanced study might not increase understanding of basic concepts
- A coherent conceptual framework is not typically an outcome of traditional instruction
- Growth in reasoning ability often does not result from traditional instruction
- Teaching by telling is an ineffective mode of instruction for most students

The solution to these difficulties is to change both the methods of instruction and assessment. Students must be intellectually active to develop a functional understanding so questions that require qualitative reasoning and verbal explanation are not only essential for assessing student learning but are also effective for helping students learn. In addition, scientific reasoning skills must be explicitly cultivated. Persistent conceptual difficulties must be explicitly addressed in multiple contexts and students need repeated practice in interpreting physics formalisms and relating them to the real world. Students need to participate in the process of constructing qualitative models and applying these models to predict and explain real-world phenomena.

Physics Education Research is thus a systematic activity of assessing where difficulties lie and finding instructional methods to overcome them. The methods described

above take time and often understanding is achieved at the expense of coverage. Perhaps it is desirable to sacrifice content for improved student understanding in the USA, where nearly all university students are expected to study some physics, even if it is only one module, but in the UK, physics is usually taught within a concentrated and dedicated degree programme accredited by the Institute of Physics. Students are exposed to a prescribed minimum body of knowledge which includes the five core areas of electromagnetism, wave phenomena, classical and quantum mechanics, statistical physics and thermodynamics, and properties of matter. To the extent that misconceptions of basic concepts exist among students, it is likely that the problems faced by US academics are similar to the problems faced by academics in the UK, but to what extent content can be reduced in favour of improved understanding is not so clear.

The purpose of this paper is to show that the deficiencies in traditional methods identified by PER, together with the solutions, are firmly in line with current cognitive thinking on learning and teaching. In particular, the SOLO taxonomy (structure of observed learning outcomes) developed by Biggs provides a direct explanation of many findings. Herrmann's quadrant model of thinking, which is pragmatic metaphor that has been applied very successfully to business, is shown to complement SOLO and the synthesis of the two leads directly to a cognitive model of problem solving which can be taught to, and used metacognitively by, students. The implications for course delivery by conventional lectures are discussed in order to suggest alternative means of improving understanding whilst maintaining coverage.

### **COGNITIVE BACKGROUND: SOLO**

SOLO is an important application of cognitive theory to modern education. In order to place SOLO in context, it is necessary to look into some of the preceding work in cognition.

Halford (5) has looked into cognitive development in terms of problem solving ability, ie deductive thinking or the process of drawing inferences. Halford has presented a complex flow diagram to illustrate the thinking involved in solving a problem, but in essence it resolves into a three-step process first developed by Craik in 1943 (see 5);

- translate the problem into an equivalent model
- operate on the model
- re-translate back to the physical situation

This coincides with the three-step model of mathematics that most physicists would recognise as descriptive of the relationship between maths and physics, which involves expressing the physics in mathematical terms, operating on the mathematics, and finally, interpreting the mathematical solution in terms of physics. Halford's ideas on cognition would therefore appear to be directly applicable to physics education, especially as he uses logico-mathematical operators to define the different stages of cognitive development.

Halford identified three developmental stages and three meaningful levels of thought corresponding to the complexity of operations that can be performed. Level one is limited to relations between pairs of objects. Level two allows for binary operations, that is using two pieces of information together to derive a third, and level 3 corresponds to compositions of binary operations, ie where three or more pieces of information are used together. Halford suggests that level three cognitive functions are well developed by the age of 17–19, which corresponds to first year university entrants. We should therefore expect all our students to be able to demonstrate the highest levels of cognition by considering several pieces of information together and

drawing inferences from them. As we know, this is not always the case. Nor is it the case that students have mastered the problem solving aspects of mathematics in physics.

Biggs (6) recognised that cognitive tests such as those used by Halford require a background knowledge of some sort, and student responses simply indicate how well this material has been learnt and understood. In short, what is measured are actually learning outcomes. Cognitive development is hypothetical in so far as it is nigh on impossible to measure it without recourse to something that has been learnt. The complex relationship between how well material is first encoded by reading or listening and how well it is subsequently reproduced means that cognitive structure cannot be reliably assessed.

The origins of SOLO lies with work on younger age groups, but it is applicable to all ages. One of Biggs' examples, a poem called 'Spring and Fall – to a young child' by Gerard Manly Hopkins (GMH), which is in fact quite difficult to interpret, illustrates learning outcomes from students around 20 to 21 years of age. The responses ranged from a literal interpretation with no generalization, to some generalization bounded by the context, and finally to a description of the poem as a metaphor in which the context is seen simply as a vehicle for conveying the central message. Generalizing to this last level represents a high level of cognitive functioning, but only those who had an interest in poetry and had studied it at university were able to present this sort of analysis. Clearly, analysis is underpinned by knowledge.

It is a necessary condition of being able to demonstrate high level cognitive functioning that students must acquire knowledge. Lectures are a very effective means of delivering it, but they not so effective at delivering understanding. The principle of constructive alignment described at the beginning of this paper holds that the student

must develop this understanding through engagement with the subject matter, and PER shows the same. Students who have developed an understanding should be able to demonstrate high level cognitive functioning, but weak students who might have learnt a lot but can apply it in only limited circumstances will only be able to demonstrate knowledge. The SOLO taxonomy provides a means of differentiating between these cases by defining understanding in general terms independent of discipline. There are five levels: prestructural, unistructural, multistructural, relational, and extended abstract. In a prestructural response the answer is confused or the question is simply repeated. A unistructural response focuses on a single fact or concept, multistructural on several unrelated facts or concepts, relational ties the various components together, and extended abstract generalises from the given to the new.

Knowledge used in this way is 'functioning'. In its most basic form knowledge is either declarative or procedural. The former is propositional - as the name implies it is used to declare this or that - and the latter is knowledge gained through repeated practice of procedures and doesn't necessarily imply understanding. To a great extent mathematical knowledge is procedural for the physicist. It is acquired through repeated practice, though of course there is an element of declarative knowledge. When these two - procedural and declarative - are combined with a knowledge of how and when to use them they become functioning. PER and constructive alignment are in agreement in so far as both stress that intellectual engagement is essential for learning, and that assessment has a role to play. PER has shown how to achieve functioning knowledge across a range of topics, but room is made within the class for intellectual engagement and functioning knowledge therefore comes at the expense of the range of declarative knowledge. Engagement in the students' own time, through, for example, formative assessment should have a similar effect but without detriment to the course coverage.

## A MODEL OF LEARNING

It is quite natural to regard these cognitive levels as hierarchical, so that a relational response is seen as representing a higher level of thought than a unistructural response. For example, extended abstract is more likely from a postgraduate physicist rather than an undergraduate except perhaps in problem solving, where necessarily the idea is to synthesize something new from given information. Problem solving is an important skill in physics and the subject will be revisited after the development of an effective learning model.

It is important not to confuse the level of the subject with the level of the response or the ability of the student. Some of the unistructural and multistructural responses to GMH came from people who would be considered able and intelligent in their own fields, so interest and motivation, as well as prior learning, are important factors which determine to a great extent how information is interpreted. This can be at a unistructural, multistructural, or relational level but this is not necessarily how it will be conveyed some time later. A multistructural view can only be transformed into a relational view if a deliberate attempt is made to relate the disparate components. If little or no thought is applied the output will be at a lower cognitive level. PER supports this directly with the observation that students' epistemological views influence strongly how well they learn physics (7). Three typical views are: learning physics is about retaining formulas and problem-solving algorithms; learning involves relating fundamental concepts to problem-solving techniques; and, learning involves building one's own understanding. The first of these is clearly multistructural, the second is relational, and the third is extended abstract in so far as the student attempts from the outset to build something new from what has been given.

Thus PER confirms the premise of SOLO. The cognitive level at input determines the

cognitive level at output, as students who perceive physics in a multistructural manner are very unlikely to develop a higher cognitive view. It would seem necessary, therefore, to alter the way that some students think about physics. Unfortunately, SOLO, as the name implies, is concerned with classifying observed outcomes. Although the same terms can be used to classify inputs, SOLO itself provides no guidance on how perceptions at the input stage might be changed. First it is necessary to identify a cause, and though motivation is identified as one factor it is by no means clear that this is the main, or only reason, that information is encoded at a particular cognitive level. An alternative model of thinking provides some insight.

Herrmann developed a four-quadrant model of thinking in the 1970s whilst working as a human resources manager with General Electric in the US (8). It is based on the celebrated left-right split in the brain with a further subdivision based on the evolutionary structure of the brain. This leads to four quadrants, each of which metaphorically describes a particular thinking pattern, but it is not suggested that thinking is located in these physically distinct areas. Moving anti-clockwise, the upper left, A, is analytical and logical, the lower left, B, organisational, the lower right, C, emotional and empathetic and concerned with personal relations, and the upper right, D, is strategic but encompasses the artistic and creative as well as conceptual thinking. The dominance of one quadrant or another is not a matter of intelligence but simply of personal characteristics. Each of us prefers to think in one or sometimes two particular quadrants and will tend to apply this type of thinking to new situations even when it is not appropriate. Students' epistemological views of physics described above can be related respectively to quadrants B, A and D therefore probably reflect their natural thinking patterns (called by Herrmann 'brain profiles') as much as any prior conceptions developed at school.

There would appear to be some correspondence between the cognitive levels of SOLO and Herrmann's model. The organisational and analytical quadrants correlate with multistructural and relational, and possibly extended abstract corresponds to aspects of the strategic quadrant. However, Herrmann stresses preferences whereas SOLO implies a hierarchy. None-theless, the quadrant model can explain the situational aspects of cognitive encoding implied in Biggs' work. A logical and analytical mind may well be unable to interpret the metaphors contained in GMH, hence the lack of interest and the consequent multistructural responses from otherwise able people. Hence, an effective model of learning is to describe the input in terms of preferred thinking and the output in terms of SOLO. It is more important to ensure that material is delivered in a way that can be understood by students with different thinking patterns than to try directly to alter their perceptions of physics. Otherwise there is a good chance that students will not build up sufficient knowledge to be able to develop different modes of thinking.

This model has two very important implications for the delivery of any higher education programme, not just physics. The first concerns effective communication. If the audience is characterised by different thinking styles the message must contain information encoded in ways that each can take something from it. Initially, the collective brain profiles of first year undergraduates is likely to contain a good proportion from at least three of the four quadrants (organisational, analytical, and strategic). Possibly some students will also exhibit a dominant empathetic brain profile, but, these are probably better suited to people oriented activities and probably will not last the course. By way of example, Herrmann has compared the collective brain profiles of entry-level undergraduate engineers at a college in the US with those of Faculty. Among the students there was an even mixture of all four quadrants, but the Faculty profiles resembled very much the average characteristics of

professional engineers in which the analytical quadrant dominates, perhaps even at the expense of some creativity. Inevitably some selection, as well as development, occurs from student to professional.

If something similar happens with physicists we can expect a shift towards the two quadrants that tend to be dominant in professional physicists, viz. the analytical and the strategic. At the later stages of a course it will be reasonable both to deliver and assess material at a predominantly relational level but in the earlier years material should ideally be delivered at several levels. The PER finding that persistent conceptual difficulties must be overcome by teaching in multiple contexts is an expression of this. The single concept is unistructural, the several different contexts is multistructural, and there may be a relational element as well. Within a single lecture the unistructural level would emphasize the single most important idea, the multistructural level would identify other important ideas, and if these can be linked by a concept the relational level is supplied. Students will take away the information most appropriate to their own thinking.

The second implication relates to group work. Herrmann has shown that groups composed of members with similar thinking styles will rapidly converge upon an agreed course of action, whereas groups constructed from representatives of all four quadrants will take as much time as is allotted, and possibly more, to air a range of possibilities. Indeed, they might not even come to a conclusion. Within SOLO Biggs has also related the cognitive levels to three categories of mental operation or function, one of which relates to arriving at a decision. At the lower cognitive levels decisions are reached quickly at the expense of consistency, but at the extended abstract there is a strong need for consistency, sometimes at the expense of a firm decision. A comparison with group whole-brain thinking implies that extended abstract is also whole-brain thinking.

In order to develop extended abstract thinking (problem solving), students need to mimic

group behaviour, which is to look at the problem in a variety of different ways: unistructural, to identify the most important idea; multistructural, to identify and organise the separate components; relational, to analyse and link the components together; strategic, to identify wider aspects and possible courses of action; and finally to synthesize and solve. In terms of quadrants, the student must organize, analyze, empathize (where necessary) and strategize. The student has to switch metacognitively to a different mode of thinking as the need arises. Herrmann calls this 'situationally whole-brained' thinking, as it seems that true whole-brained thinking occurs in only 2.5% of the population. These people show equal strength in all four quadrants, but each of us can learn and develop our thinking in other quadrants. Group activities can help students to learn physics, but they also serve as exemplars of problem solving.

## CONCLUSION

PER has been shown to be consistent with both the SOLO taxonomy and quadrant model of thinking. A cognitive model of physics teaching has been established from the synthesis of the quadrant model and SOLO. The main findings of this work are:

1. Knowledge learnt in lectures is declarative, but this in itself is necessary.
2. Functioning knowledge is developed only if students engage with the subject.
3. Material should be taught at several cognitive levels.
4. A clear problem-solving strategy emerges from the synthesis of SOLO and quadrant thinking.
5. Group work provides an exemplar for the development of problem solving skills.

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