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Title
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Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 4(0)

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Publication Date
1982

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How novices solve physics problems

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Abstract - The paper outlines ten claims about the performance of novices solving problems in physics. The claims are then evaluated from the literature, and from the results of a study where synchronised audio tape and paper and pencil working records of novices solving kinematics problems were made. Some alternative methodologies for investigating these claims are discussed and the future direction of the work indicated.

Introduction - The longterm objective of this study is to design instruction to improve physics problem solving. Various claims about how novice students go about solving physics problems can be made. Here are some of them.

1. Novices solve physics problems more slowly than experts and pause more frequently between the retrieval of successive equations or chunks of equations than experts do.

2. Novices have erroneous ideas about basic physics concepts.

3. Novices make meta statements (comments about the problem solving process).

4. Novices never check back or use real world checking.

5. Novices work backwards.

6. Novices don't apply physical intuition to a problem before actually trying to solve it.

7. Novices don't possess rich internal representations for complex problems.

8. Novices are not goal directed.

9. Novices use consistent strategies in problem solving.

10. Novices can be taught helpful problem solving strategies.

These claims will be discussed using two sources of evidence - reports in the literature, and the results of a study of solution protocols in kinematics. The claims are stated in order of certainty. This paper will take each claim in turn and assess its validity. Some are as yet unsubstantiated. Future work which might substantiate them will be discussed.

The literature - Previous empirical studies of how physics problems are solved have examined the knowledge structures discussed in the basic concepts (Shavelson 1974, Reif 1981), examined students prior conceptions of the physical world (misconcepts) (Champagne & Klopfer 1980, Gilbert & Osbourne, di Sessa 1981) and examined solution protocols (Larkin et al, 1981).

The Cyclops study - The study reported here involved the collection of solution protocols and their analysis in terms of problem solving strategies displayed and misconcepts revealed (Scanlon, 1981). Some recordings of Open University (OU) first year students attempts to solve physics problems were made. The equipment consisted of a summa graphics bitpad and microphone connected via an interface box to a stereo cassette recorder. This equipment based on the OU's Cyclops technology allows recordings of pencil and paper working to be made on one track of the cassette tape while the other track records any words spoken during the process. The equipment has been used to record children's mathematical behavior (O'Shea & Floyd, 1981). The system combines in a convenient form the students voice with a synchronised dynamic record of what he or she writes. This study has established that the system was suitable for recording the mixture of handwriting, diagrams and numbers present in a typical adult physics problem solving protocol.

The subjects were seven first year Open University students who had just completed three weeks of study on elementary mechanics. Their backgrounds varied from no previous experience of physics to A level physics. Open University students are adults returning to study after some work experience. In the attempt to attain an understanding of problem solving skills in physics there are advantages in using adult students. Skill at solving physics problems is not a natural competence but a learned skill - and one learned with considerable difficulty. Adults language competence is fully developed so the notorious difficulty of achieving verbalisation in protocols should be simplest with them (Horowitz 1980). The problems selected for the students were simple kinematics problems. From the replay of the Cyclops tape the sequence of operations, timing information on each individual step, and the verbal protocol indicates problem solving decisions made.

Discussion of the claims

1. Novices solve problems more slowly than experts, and pause more frequently.

Expert and novice protocols have been compared to highlight the differences (Simon & Simon, 1978, Larkin, 1981). Experts have been found to be 4 times faster at solving problems than novices. The pause times between the retrieval of successive equations or chunks of equations were quite different (Larkin 1979). Experts produced streams of equations without pausing while novices paused most of the time. In the Cyclops study the students experienced many difficulties with the problems.

2. Novices have erroneous ideas about basic physics concepts.

Trowbridge (1979) describes students problems with the concepts of velocity and acceleration. The weaker students in the Cyclops study also had a very hazy notion of acceleration and constantly confused it with velocity. Velocity they confused with speed and average speed. See Fig. 1. However, the fact that students have an imperfect understanding of some of the concepts they need to use doesn't seem particularly surprising. When their understanding drops below a certain level - its obviously the most important thing to worry about. If you can't tell acceleration from velocity you're going to have trouble doing problems about either. However, what does it mean to understand a concept completely? Wouldn't some level of understanding be good enough for all practical purposes? We have to solve problems in real life in the absence of complete understanding. Some of the 'misconcepts' research seems also to draw questionnable conclusions. In Andy di Sessa's (1980) study of how high school students manipulate a dynaturtle he says reveals misconcepts about force and acceleration - but these students score highly on conventional tests. It reveals something about the physics not having got 'into the musculature' but who plays tennis using Newton's Laws?

3. Novices make meta statements

Simon & Simon (1978) observed the difference in the number of meta statements made. By meta statements they mean comments made by the students about the problem solving process. Experts made fewer meta statements than novices who made more frequent comments on errors made, the physical meaning of an equation, or overall direction. This finding is on the surface surprising but may be to do with the novice voicing uncertainties that an expert doesn't share. In the Cyclops study students made many such comments.

4. Novices never check back

The weaker students in the Cyclops study made many mistakes due to not carefully reading the problem statement. They misread distances for speeds, final speeds for average speeds etc. and despite the fact that these mistakes led them into numerous problems never looked back to check. Having struggled through to an answer to the problem the novices never checked back to see whether the answer made sense in terms of the original problem statement.

The better students in the Cyclops study highlighted the behaviour of the novices. They checked back to various stages - both during the problem to make sure they'd solved a sub-problem checked back to see if their answer made sense in terms of the numbers given in the problem. They also tried various ways of doing a problem and if something didn't seem to be working out they were prepared to start again in a different direction. They seemed less prepared just to plod on regardless of whether the solution path they'd chosen seemed to be successful or not.

5. Novices work backwards

The most contentious difference quoted in the literature is the difference in solution path - 'working forward - working backward' (Simon & Simon 1978). The expert works from the information given in the problem, producing equations which can be solved using the information given. The novice starts by generating an equation which contains the unknown he is trying to find and works backward. This finding seems strange but may be is explained by the confidence felt by the expert that the problem is soluble. This behaviour was not observed in the Cyclops study. Students mostly started by writing down the equations they knew.

6. Novices don't apply physical intuition

Experts seem to apply to prior qualitative analysis or physical intuition to the problem before actually starting to solve it. What seems to characterise this analysis is the ability to represent the problem physically in terms of some real world mechanisms (Larkin & Reif 1979). If novices relied on their physical intuition they might create a false analysis, (as they have erroneous ideas about basic physics concepts). In the Cyclops study among the novices no connection with the real world in solving the problem was apparent.

7. Novices don't categorise problems into types and don't possess rich internal representation

The expert has built up a set of fundamental sets of subroutines for basic types of problems and this classification into problem types takes place very quickly (Chi, Feltovich & Glaser 1980). An investigation of this appears in Chi, Glaser & Rees (1981). In answer to the question 'how does an expert construct a more efficient subroutine for a complex problem?' they reply that 'the facility lies in the rich internal representation the expert has generated'. The Cyclops study did not investigate this claim.

8. Novices are not goal directed

An important difference between experts and novices is that experts are confident enough that they will eventually succeed to be willing to try out various approaches. In the Cyclops study, the novices were playing a game of pretending to solve the problems. However they knew that really they couldn't so it didn't really matter what they wrote down. They appeared to conspire with the experimenter to pretend that they were looking for a solution path and made all sorts of meta comments. "I see. . . well suppose I try", but they were just trying to get any answer so that the problem will go away.

9. Novices use consistent strategies in problem solving

Several of the weaker students in the Cyclops study had 'a way of doing problems'. The protocols are littered with statements like: "This is how I always do problems" "I always draw a diagram" or "write down all the equations I know" or "write down everything in sentences". The last example is very interesting and came from a student who has a great deal of trouble with mathematics. She says that she never knows whether something makes sense unless she can write it down in the form of a sentence so this is how she argues her way to a solution.

The surprising result of the Cyclops study is that the poorer students did seem to be exhibiting some sort of consistent way of coping with being asked to do physics problems which they didn't know how to do. This is reminiscent of Kathy Larkin's experience of adults doing arithmetic problems.

They could remember how to do some things - they had 'Islands of Knowledge' (Larkin, 1978). The adults in the Cyclops study had 'Islands of tactics'. They were not basing their behaviour on understanding of physics but on some sort of 'coping strategy'.

Discussion - The first four claims seem incontrivertable. The fifth is substantiated in the literature but seems in contradiction to the eighth claim from the present Cyclops study that novices aren't goal directed. They only occasionally conspire with the experimenter to pretend they are. The sixth and seventh claim are also substantiated though what 'a rich internal representation' means has yet to be defined or demonstrated. Most of these claims are in fact disclaimers - they're statements about what the novices don't do. The ninth claim is made on the basis of the present study and remains to be fully substantiated - and it is a positive claim. The tenth claim is in fact a pious hope. Larkin & Reif (1979) have designed instruction based on their models of expert physics problem solvers but the effects of the instruction have not been extensively tested.

The Cyclops study will be developed to investigate how best instruction can be designed to improve the performance of novice physics problem solvers. Many of the claims discussed above while well substantiated don't seem to provide many clues about how to do this. Correcting erroneous ideas about basic physics concepts is highly relevant and may even be related to the question of physical intuition and rich internal representation. (Reif & Heller 1982). Also important are questions of strategy checking back etc. To proceed further models must be built which reflect the features of novice problem solving which instruction would be designed to remedy.

Three options for this modelling are possible.

- construct models based on the means ends knowledge development distinction (e.g. Larkin & Simon, 1981)
- take an expert system and alter it to generate the types of errors which students make (e.g. Priest 1979)
- construct models based on the notion of a direct translation model of physics problem solving.

The first option is one which has already been explored. Larkin, McDermott, Simon and Simon (1980) describe two related models - the knowledge development model which simulates expert behaviour and the Means End model for novices. These are a development of the Simon and Simon working forward and backward models which solve dynamics (as well as kinematic) problems and are more elaborated to simulate behaviour more closely. The similarities between these two methods are more important than the differences. Both require an overt statement of goals. In the Cyclops study the novice students didn't have goals however. These models seem too sophisticated to ever generate the types of error seen in the study.

A similar objection can be raised to the second option. Mecho is a program written in Prolog which solves a wide range of mechanics problems from statements in English (Bundy 1979). Both Mecho and also Isaac (Novak 1976) could in principle be altered to generate the types of errors described above (Priest 1979). However the behaviour of these novices seem much too inexpert for that to seem psychologically valid.

We propose to take a direct translation program like STUDENT (Bobrow 1968) which operates in the domain of algebra story problems and alter it to handle these limited physics problems. Students in the Cyclops study confused velocity with acceleration, treated any quantities in the problem almost as being completely inter-changeable. This program would be able to generate such errors and account for many of the errors observed in the study. If such a model could generate a large proportion of the errors observed, this would provide strong evidence of the need for instruction to correct the misconcepts.

Assuming this activity was successful how could it be used to advantage to design some physics instruction? There are two complementary approaches.

Firstly it is necessary to build confidence. The consistency of strategies observed among novices is in fact a weakness which needs to be corrected. They were probably suffering from a lack of confidence which would allow them to explore alternative methods of solution. They need more opportunities to explore these.

Secondly misconcepts should be corrected. The literature on computer games applied to physics (White 1980) is attractive. These provide a way of combining an aid for the exploration of concepts with a way of flexibly exploring how to solve a problem that might be enjoyable. The modelling activity described above would provide a basis on which the exploration of concepts in the game would be designed.

Conclusion - Many claims about how novices solve problems have been made. By using synchronised audio tape and paper and pencil working records, it has proved possible to investigate more carefully the extent to which some of these claims are true. A stronger test will be to base instructional material directly on the types of misconcepts and affective features associated with this view of novices physics problem solving behaviour.

Acknowledgement - We are grateful to Jon Slack for helpful comments on drafts of this paper and to Andy di Sessa, Paul Feltovich, Jill Larkin, Fred Reif and Richard Young for helpful discussions. Our thanks are also due to Claire Jones for typing this paper.

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Fig. 1 Seven types of errors identified in the Cyclops study

1.	Confusing the meaning of the various terms used (velocity with acceleration, velocity with speed, speed and acceleration with position, average velocity with instantaneous velocity)
2.	Incorrect interpretation of the word 'uniform'
3.	Misreading of items in the problem statement
4.	Drawing misleading diagrams
5.	Incorrectly remembering equations of motion to be used
6.	Substituting the wrong values into the equations of motions
7.	Misunderstanding the meaning of a variable in an equation