Cognition of an expert tackling an unfamiliar conceptual physics problem

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Abstract. We have investigated and analyzed the cognition of an expert tackling a qualitative conceptual physics problem of an unfamiliar type. Our goal was to elucidate the detailed cognitive processes and knowledge elements involved, irrespective of final solution form, and consider implications for instruction. The basic but non-trivial problem was to find qualitatively the direction of acceleration of a pendulum bob at various stages of its motion, a problem originally studied by Reif and Allen. Methodology included interviews, introspection, retrospection and self-reported metacognition. Multiple facets of cognition were revealed, with different reasoning strategies used at different stages and for different points on the path. An account is given of the zigzag thinking paths and interplay of reasoning modes and schema elements involved. We interpret the cognitive processes in terms of theoretical concepts that emerged, namely: case-based, principle-based, experiential-intuitive and practical-heuristic reasoning; knowledge elements and schemata; activation; metacognition and epistemic framing. The complexity of cognition revealed in this case study contrasts with the tidy principle-based solutions we present to students. The pervasive role of schemata, case-based reasoning, practical heuristic strategies, and their interplay with physics principles is noteworthy, since these aspects of cognition are generally neither recognized nor taught. The schema/reasoning-mode perspective has direct application in science teaching, learning and problem-solving.

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Introduction

Conceptual understanding and problem-solving are two important goals of physics courses, with much instruction and assessment time devoted to them. There are many studies on student problem-solving, and others on comparison of novice and expert performance on both qualitative and quantitative problems. Hsu et. al.[1] recently provided a useful review of work on problem solving in physics. Comparing expert and novice performance on the same problem gives insights into ideal or 'normative' problem-solving; good expert performance indicates the nature of 'final' expertise and presumably represents the goal state for students, and comparative studies show how novice thinking differs from this.

However such studies are limited for understanding expert cognition more broadly, since what is a 'problem' for a novice long ago became a familiar 'exercise' for an expert. The expert's solution will likely resemble the polished final-product worked examples presented in textbooks and teaching. However this does not reflect the actual cognitive processes that occur along the way, especially when the expert is in unfamiliar territory, which is the situation a novice usually faces.

The more interesting question from a cognitive perspective is how an expert thinks when faced with an unfamiliar type of problem, though one for which he or she does have the requisite knowledge. This then becomes a 'real' problem for the expert. In this sense something is a problem when one doesn't initially know how to do it, and problem-solving is seen as "what you do when you don't know what to do" [2].

Thus our question of interest is not how an expert solves a problem once it has become part of standard repertoire, but how he or she thinks when tackling a task without knowing how to proceed. To this end we investigated and analyzed the cognition of an expert tackling a conceptually demanding qualitative physics problem. We use the term 'expert' in both nominal and operational senses; in this study the expert 'Jack' was a PhD physicist and experienced physics instructor, but also with demonstrated proficiency in the problem domain.

Note also that our aim here was not to study the thinking of a wide range of experts but to trace the cognition of an individual expert in considerable detail in a case study, to elucidate its nature and complexity, even for a problem for which they were well equipped.

In this paper we present part of a case study of one particular expert, describing the zigzag thinking path and interplay of reasoning modes, knowledge elements cases and schemas involved. The fact that the cognition revealed may to some extent be idiosyncratic to this particular expert is not the issue here; rather the aim is to demonstrate how for each individual cognition has multiple facets, many of them not generally recognized. The complexity of actual cognition contrasts markedly with the systematic principle-based solutions we usually provide to students.

It is important to know how experts think in order to teach more effectively and give problem-solving feedback to students. Simply 'going over' the final normative solution with novices is unlikely to be sufficient, if that is not the way that those proficient in the field actually think along the way.

Problem characteristics

An appropriate problem for studying cognition would involve good conceptual understanding, be non-trivial but not inherently difficult, and of a type the subject had not encountered before but in a domain where he or she was broadly proficient. The pendulum problem originally used by Reif and Allen [4] has these characteristics. Figure 1 illustrates the situation.

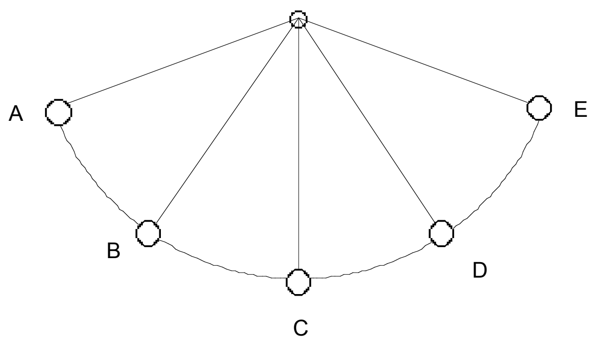

Figure 1. A pendulum bob swings in the arc shown. Five different positions of the bob are labelled.

The problem asks whether or not the bob has an acceleration at the various labeled points of its motion, and if so to find qualitatively the *direction* of acceleration. In a sense it is not a 'single' problem but a set of variant cases, particularly useful for studying cognition and its context-dependence

The expert subject was familiar with pendulum motion and the forces acting, and possessed all the kinematics and/or dynamics knowledge needed. He had solved many problems involving acceleration before, but none involved its direction in curved motion. Thus this problem was unfamiliar. We mention that there is a straightforward and consistent way to solve this problem, but we give it only after describing how the expert thought.

Research methods

The methods used in this study were to some extent unconventional in that besides interviews they included introspection, prompt and delayed retrospection, discussion and reported metacognition, rather than think-aloud verbalization during problem-solving. Thinking initially proceeded fairly naturally and uninterrupted. The term introspection may perhaps come somewhat laden historically, but seems a good term to describe self-awareness of the problem-solving processes involved here. The study was also unusual in that one of the investigators was also the primary subject for the case study, so that self-reporting was involved to a considerable extent.

The rationale for and validity of the methods will not be addressed here, in a short paper focusing on cognition; these issues can best be dealt with in a longer paper. Here we simply note that the methods proved very valuable for obtaining detailed fine-grained data and elucidating cognition in depth, and worked very well for the purposes of this study. We were able to reveal aspects of thinking difficult to obtain less directly. One reason that cognition can be captured quite well in this research situation even by delayed retrospection is that it doesn't 'go away' – the same problem tends to cue the same thinking, since this arises in large part from the subject's established schemata interacting with the problem features. We note that the validity risks of self-reporting are somewhat different from but probably no greater than those for secondary reporting and interpreting, and that there are a variety of kinds of research in which researchers are also involved as participants.

Conceptual framework for analyzing and interpreting cognition

Our conceptual framework for understudying cognition in problem-solving *emerged* during this and related studies we have conducted. We view the conceptual framework itself as one of the important outcomes of these studies. Having generated a basis for analysis we were then able to interpret cognition for the pendulum problem in terms of a number of theoretical ideas. These included reasoning modes of four main types, knowledge elements, principles, procedures, cases, schemata, activation and interference, metacognition and epistemic framing.

We identified four main types of reasoning strategies, as follows.

• In *principle-based reasoning* (PBR), problem solutions are obtained by a systematic application of fundamental physics concepts and principles.

• In *case-based reasoning* (CBR) one draws quickly by association on features of recalled similar cases. One retrieves previously compiled knowledge subassemblies, and tries to adapt these to the current case, rather than constructing a principled solution from scratch. Kolodner [3] discusses case-based reasoning in several fields.

• *Experiential-intuitive reasoning* (EIR) involves fairly primitive intuitive ideas or phenomenological primitives (p-prims), arising from life experiences with the world and how things behave. It is more a spontaneous than conscious mode of reasoning, and works reasonably well in situations close to experience, but may lead to error if used inappropriately to a situation

• In *practical heuristic reasoning* (PHR) one uses general experience-based strategies such as 'rules of thumb', educated guesses, or 'common sense', that can help one come up with a possible problem solution that may possibly be close to correct.

In addition, the *schema* concept proved very valuable to our study. A schema is a mental structure associated with a particular aspect of the world. In learning a concept one builds up and organizes knowledge as an elaborate network (schema) of connected knowledge elements, exemplars, ideas, properties, relationships and cases, which represent one's current understanding of the concept.

Cognition for the pendulum problem

We now give an interpreted narrative account of the thinking of expert Jack as he tackled the pendulum problem. This was obtained using the methods noted, and interpreted in terms of the theoretical ideas listed. It is useful to consider the problem-solving process in recognizable *episodes*, although actual thinking goes back and forth. The account given here is constrained by space and is by no means as detailed as the actual account produced, and includes only limited analysis comment.

Thinking about the problem

After the problem was presented, Jack thought silently for about a minute. He realized he had never encountered this kind of question about acceleration. So he first looked at the situation more broadly than the specific problem posed, visualizing the system behavior quickly (easy since pendulums were so familiar to him). Specifically, the bob moves in an arc, constrained by the string, speeding up or slowing down at various stages. The bottom and end points were special cases. As to forces, the only forces acting were gravity and the string force.

Jack then focused on the labeled points to see 'what was going on' at each. He immediately 'set aside' the two right-hand points, since he saw them as being symmetric to the left points. 'What was going on' included for him knowledge of both the motion and the forces acting on the bob to produce it. He sensed that the curved path and changing speed would somehow complicate things, and after more detailed thought about forces, that the resultant of the two forces would be changing during the motion . . . uh oh. These broad insights were drawn largely from his broader expertise. Having thus 'set the scene' about the system he turned to the specific question about acceleration and wondered how to figure this out. He had already decided he need consider only three points, but which to start with? The end points would likely be easiest, while the intermediate case would definitely be hardest. Jack thought of starting with the left end point but then chose the bottom point.

The bottom point

i. Activation of linear motion schema

Jack wasn't fully aware of it at the time but on retrospection said that there were probably two reasons for being comfortable with choosing the lowest point. Firstly he 'knew' that the speed would be the same left and right of this point, implying no acceleration. (Actually incorrect). Secondly, this seemed consistent with there being two equal and opposite forces on the bob, gravity and the string force, both vertical and thus not influencing horizontal motion. Jack was actually mixing static case knowledge with dynamic here, but it only lasted a moment before he caught his error.

It seems that Jack had started out by perceiving the motion in the small region around the bottom point in terms of his existing schema for 'linear motion', and was trying to fit the known results for this case. Schemas are not only ways we understand things, but also ways we *perceive* and frame things.

ii. Activation of uniform circular motion schema

After initially concluding that the acceleration would be zero at the bottom, Jack then wondered how the fact that the path segment was in fact slightly curved might affect things. This immediately cued a relevant case result from uniform circular motion, namely that a force toward the center of the circle was involved. He then simply dropped the linear motion schema. Although it had activated spontaneously at first, and he'd tried to 'fit' it, it was not appropriate here. Thinking now in terms of both force and motion, there must be a (centripetal) acceleration, pointing upward. Two further pieces of compiled case knowledge now 'popped up' in quick succession. Firstly that for a pendulum the curved motion was in fact *not* uniform; his (heuristic) rationalized response to this was that it would 'likely not matter' here. Secondly, he vividly recalled a worked example of non-uniform motion in a vertical circle, picturing in his mind an entire diagram from a textbook; this part of his schema even included differing force diagrams at the highest and lowest points, plus the fact that it turns out that the string tension at the bottom exceeds that at the top by a certain (unremembered) amount. The latter knowledge element was retrieved only briefly; it is not relevant for the pendulum, but 'came with the territory', so he didn't pursue it, recognizing it as a sideshow. However, by transferring elements from this previous example he certainly had a knowledge subassembly ready to fit in place almost as a unit.

Note that for the bottom point Jack's route to acceleration was mostly via force. He understood forces, force diagrams, and compiled case results for circular motion. Forces loomed large in his thinking, even though they were not asked for in the problem. There are good reasons to expect this, particularly for experts, since it forms a large part of their knowledge of dynamics. Just as noteworthy is that Jack worked on an acceleration problem without actually invoking the basic conceptual meaning of acceleration (as velocity change). This is case-based reasoning par excellence, rather than principle-based. His reasoning did give the correct answer, though the route he used is not really necessary as we will see. It is a roundabout and case-specific way to the goal, and also will not work at the other points. Jack was very certain of the correctness of his answer at the bottom point.

Other points on the path

Jack next turned to the (special case) left end point A, and after that the (general case) intermediate point B. In a short paper we cannot go into a similar detailed cognitive narrative for each of the labeled points, but we note that it was fascinating that the approaches, cognitive paths and knowledge elements involved were quite different for each of these cases, even though the same question was being addressed! Furthermore, as we will see, all the cases can be solved in the same way from basic principles, but this is not what Jack did, though he did reach correct answers.

Principled solution from basic definition

It is interesting to note that this pendulum problem can be answered in the same straightforward and consistent way at all points by the application of the definition of acceleration in this two-dimensional situation.. The definition of acceleration is "the rate of change of velocity", or symbolically $\mathbf{a} = \Delta\mathbf{v}/\Delta t$. This vector equation implies a procedure for determining acceleration from motion via velocities: one considers the velocity change $\Delta\mathbf{v}$ between t two adjacent points in the motion, occurring a short time Δt apart. In the case of the pendulum at point B for example, one draws in velocity vectors just before and just after point B, tangent to the motion, and subtracts them vectorially to get the velocity change $\Delta\mathbf{v}$. The direction of $\Delta\mathbf{v}$ then gives the direction of the acceleration. (Strictly speaking one should consider the limit as the intervals become very small). The procedure is illustrated in figure 2.

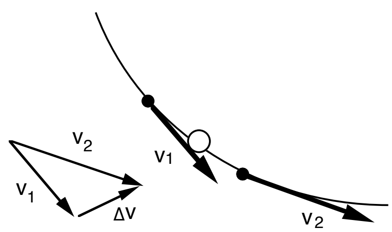

Figure 2. Velocity vectors at two slightly separated points of the motion, and the vector diagram showing how one obtains their vector difference Δv, and hence the direction of the acceleration.

This basic approach works quickly and reliably at each point of the path. Yet in practice neither novices nor experts tend to approach the problem this way, but use other modes of reasoning about the system. Reif and Allen [4] describe a range of novice and expert thinking on this and other acceleration problems.

At the end of the problem-solving session, when the interviewer pointed out the general vector procedure for determining acceleration, expert Jack immediately recognized its power and generality. This came as something of a revelation and intrigued him, and he then applied it quickly and correctly to all the pendulum positions, wondering why he had not thought of it. The knowledge was 'there' (somewhere) but was never organized, cued or used in this problem; for the most part related case knowledge was invoked along with general heuristic strategies.

Conclusions and instructional implications

The study revealed multiple facets of cognition, including multiple modes of reasoning and facets of schemata. Case-based reasoning was quite pervasive, interacting with principles, and there was clear context- and background-dependence to thinking. Cognition in tackling an unfamiliar problem seemed to proceed initially by activation of various existing schema elements from the expert's experience, related to the situation at hand. Case-based reasoning was predominantly used at each point on the pendulum path, drawing on the subject's rich repertoire of case knowledge, though different cases at each point. It was especially interesting that a principle-based approach was used by Jack in only one of the cases (the left end point) and this to only a limited extent along with other reasoning and case knowledge. Equally interesting, Jack made as much use of a force & dynamics perspective as an acceleration & kinematics perspective, even though force was not necessary to solve the problem posed; this may reflect scientists' natural penchant for causal understanding.

The fact that different reasoning strategies were used for different points of the path illustrates how cognition is strongly context-dependent with respect to problem features, and schema-dependent with respect to the solver, i.e. to a person's existing knowledge and expertise, and this seems true for both novices and experts. As expertise increases, one has more and richer schemata in one's repertoire, to activate in any given situation, and correspondingly one is more likely to draw on these automatically in approaching a problem, rather than start thinking from scratch from basic principles - as we often seem to tell our students to start by doing.

Note that the new perceptions and insights that arose from engaging with this problem will in future form part of Jack's enhanced schemata for such situations. Jack is not the problem-solver that he was before. Accordingly his cognition will likely be different in significant respects next time. So too, of course, it is with students.

Implications for instruction are that what we know about cognition has to taken seriously and dealt with explicitly in science learning and problem solving, if instruction is to align with how people actually learn, think and tackle problems. This includes addressing the various modes of reasoning observed in both experts and novices, and recognizing the role of schemata. We are unlikely to be able to help students with the crucial beginning and intermediate stages of a problem, rather than just the final solution, if we do not know how experts operate in these stages. Much of this may be fairly tacit or unconscious to instructors themselves, so an important task is to try to bring it out, making cognition more transparent.

The reasoning mode and schemata perspectives have direct practical relevance in science teaching and learning. In problem-solving, focusing solely on the desired end-product physics solution is rather limited; it is of course essential, but can go only so far addressing what is fundamentally a complex cognitive endeavor. To promote the development of expertise and the ability to tackle problems involving new situations, instruction could model cognition to a much greater extent, 'making thinking visible' in a cognitive apprenticeship sense [5]. This is by no means easy but certainly interesting and valuable.

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