Literature Review: How students learn in mechanics – the difference between experts and novices

What is the difference between novices and experts in mechanics?

In the early 1980s, Chi, Feltovitch and Glaser (Chi, Feltovich, & Glaser, 1981) had physics undergraduate as well as Ph.D. students sort mechanics problems into self-chosen categories. The result: both groups started looking for the same keywords, but while the Ph.D. students (experts) made the final organization based on the major physics principles at play, the undergraduates (novices) chose surface aspects as their categories. When asked how to solve these problems, the experts started with the physics principles, while the novices jumped directly into equations or gave general, unrelated statements. This superficial problem-solving technique of novices was also identified by other researchers at that time, for example Larkin, Reif, McDermott, Simon and Simon, 1979 (as cited in Chi, Feltovich, & Glaser, 1981), but is still the subject of recent work. Toksoy and Akdeniz (Eryılmaz Toksoy & Akdeniz, 2015) had students completely solve force-motion problems. By analysing the solution protocols, Toksoy and Akdeniz arrived at the same conclusion as Chi et al. more than 30 years earlier: Novices use a basic surface approach while experts rely on the underlying concepts.

As summarized by Priest and Lindsay (Priest & Lindsay, 1992), various researchers have rephrased this surface versus concept approach as follows: Novices use backward inference, starting from the unknown (the surface) while experts use forward inference (starting from the givens and the concept). In practical terms, this means that novices will look for equations that include the variable that they are looking for and then create additional equations. Experts, on the other hand, will identify the main concept that relates to the problem and start with equations that contain the known entities to solve the problem.

How does a novice become an expert?

In order to learn more about how novices become experts, computer simulations have been written. Some of them, the “MECHO-system” by Bundy, Byrd, Mellish, & Palmer and “PDP-10” by Jansweijer, Elshout, & Wielinga (as cited in A. G. Priest & Lindsay, 1992), were designed to only operate as novice solvers. Others started as novices, but with experience, memorizing the equations found for typical problems and recalling them in inverse order, became expert problem-solvers. Examples of these expertise-acquiring programs are the systems designed by Elio & Scharf as well as Larkin and Priest (as cited in A. G. Priest & Lindsay, 1992). The success of those computer simulations could indicate that expertise can be acquired through memorization of problem-solutions. However, the differentiation between expert and novice behaviour based on the order in which equations are generated is contested. In their 1992 paper, Priest and Lindsay (Priest & Lindsay, 1992) also published the results of a study that showed no significant difference in this regard between novices and experts. Instead, the differences identified by Priest and Lindsay were the success rate (higher for experts) and the ability for experts to plan ahead and solve the problems faster. A more recent paper by Wilson (Wilson, 2014) agrees with Priest and Lindsay's finding that experts and novices use similar problem-solving techniques. Therefore it appears that there is more to acquiring expertise than memorizing problem-solutions. Those computer simulations have simply demonstrated that through memorization, problems can be solved more efficiently.

Instead, Wilson (Wilson, 2014) explains the higher effectiveness (success rate and speed) of experts with the different perception of the relation between math and physics. In their study, experts and novices agree that math can be used to represent the relations between physical quantities. But while novices see physics as a form of applied math, experts perceive physics as a science, based on experiment and concept. Wilson argues that this difference in perception is the reason why novices are usually good in solving problems with numbers but fail in answering conceptual questions.

What are the roadblocks on the way to becoming an expert?

This struggle of students with problems without numbers is a phenomenon every physics teacher can relate to. It was repeatedly documented, for example by Mazur (as cited in Lasry, Guillemette, & Mazur, 2014), and lead to the development of the force-concept inventory (FCI) test. The FCI is a set of multiple-choice questions on Newtonian mechanics. The questions are purely conceptual and require no calculations to be solved. It is regularly given to students before and after their first physics course at university or college level to measure the learning that occurred in between. As it is widely used, the amount of FCI-data (thousands of students have taken it) surpasses most other studies on student learning in sample size. The results show that overall, traditional education does not provide a significant gain in FCI-performance (Hake, 1998, as cited in Lasry, Guillemette, & Mazur, 2014). Even worse, a meta-analysis of 13'000 FCI tests by Lasry, Guillemette and Mazur (Lasry, Guillemette, & Mazur, 2014) found that students that already performed well on their first test, tend to do better in the second FCI (46%), but students that did not perform well on the first FCI often have an even lower score on the second test (30%). The gains for the students that already did well on their first test can be easily explained. The larger the initial knowledge base is, the easier it is to integrate new concepts and the better the second FCI results will be. However, this constructivist view does not explain why some students perform significantly worse on their second FCI (at the end of their mechanics course) than on their first one. Even if a student starts with very little knowledge (at the first test), it would be expected that the performance should improve by taking a course in mechanics,

Several authors (Brault Foisy, Potvin, Riopel, & Masson, 2015; Buteler & Coleoni, 2014; Lasry et al., 2014; Lin & Singh, 2015; Smith III, Disessa, &

Roschelle, 1994) try to explain these unexpected FCI-results and the poorer novice performance in problem-solving discussed earlier. While there is a consensus on the existence of a link between performance and initial concepts of a novice, the ideas of how these concepts change when a novice becomes an expert vary greatly. These explanations range from experts overcoming, replacing, transforming and inhibiting the initial concepts (Brault Foisy et al., 2015) to using and refining them (Buteler & Coleoni, 2014; Lin & Singh, 2015; Smith III et al., 1994). Depending on how the initial student-concepts are thought to interact with the learning process, they are referred to as misconceptions, initial conceptions, intuitive conceptions, naïve concepts or simply alternative conceptions. Smith Ill, diSessa and Rochelle (Smith III et al., 1994) argue that these initial conceptions are so widespread and resistant to change because they effectively explain everyday experiences of students and therefore should not be labelled misconceptions. Smith et al. also critique that the problems used earlier by Chi (Chi et al., 1981) and Larkin, McDermott, Simon, & Simon, 1979 (as cited in Smith III et al., 1994) to distinguish between expert and novice approaches, led the novices to be less successful, not because their concepts are inherently wrong, but because the novices were unfamiliar with the situations used. Smith et al. show that novices employ approaches, not unlike those of experts, when using physics to analyse settings they know from everyday life. Smith et al. offer a possible explanation for the performance deterioration of some students. They state the hypothesis that identifying initial student conceptions as misconceptions and removing them from a student's knowledge framework could have a negative impact. Indeed, just removing the initial concepts could leave the student with nothing to work with during the second FCI-test, explaining the drop in performance. In consequence, Smith et al. promote the idea that it is not the removal of initial conceptions, but their refinement that leads to expertise. Along these lines, Buteler and Coleoni (Buteler & Coleoni, 2014) showed that working against the initial intuitions does not improve student understanding. In their study, the students instructed to ignore their initial thoughts while able to solve the problem, ended up being confused. On the other hand, the students instructed to base their explorations on their initial concepts and then gradually refining them had a true eureka moment.

Conclusion

Students do not come to the classroom as true novices. This is especially true for mechanics classes. Through interaction with the world since early childhood, the students have acquired an extensive set of concepts about how mechanics is supposed to work. While these concepts successfully explain everyday phenomena, they seem to have limited success with formal conceptual physics problems as used in the force concept inventory. The courses seem to help the students acquire the procedures to identify numerical solutions, but fail to help them make the connection with the concepts. When assessed, the student approaches look to the expert like “surface approaches”, based on memorized numerical procedures without any underlying understanding (Chi et al., 1981; Eryılmaz Toksoy & Akdeniz, 2015).

Often, teachers label the students initial conceptions as misconceptions and try to replace them with the “correct” Newtonian concepts. However, all scientists know that there is no right or wrong regarding concepts. All concepts are good in some settings but have limitations in others. Newtonian mechanics itself is actually a very good example. It performs well for normal sized objects that move with less than 1% of the speed of light. For speeds higher than 10% however, the results are inaccurate. Newtonian mechanics even fails completely when describing phenomena at speed of light or extremely small objects. These limitations lead to the development of Einstein’s special and general theories of relativity and the whole field of quantum mechanics. How come that the moment a physics instructor enters the mechanics classroom, all of this seems to be forgotten and the goal becomes to replace the “wrong” student conceptions with the “correct” Newtonian concepts?

Experimental data (case studies and thousands of FCI tests) (Chi et al., 1981; Eryılmaz Toksoy & Akdeniz, 2015; Lasry et al., 2014) show that the way mechanics is taught is not improving the understanding of all students. Even worse, there are students, that leave the classes more confused than they entered, leading to a deterioration in FCI scores (Lasry et al., 2014). If these data would be the result of an experiment on a physics theorem, a scientist would quickly identify that the theorem has limitations and needs improvement.

Yet, when it comes to teaching mechanics, most teachers do realize the issues but are resistant to change the way they teach.

Maybe Buteler and Coleoni (Buteler & Coleoni, 2014) are on the right track when emphasizing that the alternative student conceptions should be used as the starting point of a scientific inquiry and Smith et al. (Smith III et al., 1994) rightfully suspect the attempt to remove the naïve concepts from the students knowledge framework to have a negative impact. Wilson (Wilson, 2014) identified the novices to perceive physics as applied math. Could this be the result of the focus on memorizing numerical solution procedures as an easy way out of the conceptual dilemmas? Even the “expert computer programs” described by Priest and Lindsay (Priest & Lindsay, 1992) used memorization of solution procedures as the fundamental method to simulate expertise. But, as many students, those “expert computer programs” probably did not understand the concepts and would perform poorly on an FCI.

This literature review had the focus on novice-expert differences and learning in mechanics. It would be interesting to see if the situation is similar in other domains of physics, especially those where students do not bring any well tested initial conceptions to the classroom. Based on the findings by Buteler and Coleoni, the impact of different teaching strategies that build on the initial concepts should be further investigated. One idea could be to treat the student concepts equally to the concepts to be learned and then elaborate the limitations of both through experiments.

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