A summary for teachers, of

U-shaped Development of Newtonian Concepts: Implications for Pedagogical Design and Research Practice

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Abstract

In the years 2002-2004, the Learning by DesignTM group at Georgia Tech conducted an investigation of the development of qualitative Newtonian concepts as a function of time. I describe the classroom context and method for this investigation, involving the coordination of multiple measures including diagnostic quizzes, structured interviews, ethnographic observations in class and performance assessments. This paper specifically concerns the results from the diagnostic quizzes, relying on other measures as supporting evidence. I present convincing evidence of conceptual gains from that data. I also show that when looked at in more detail, there is a clear non-monotonic conceptual development process in which there is a period of apparent regression of understanding following apparent satisfactory understanding. I consider prior work on this effect from developmental psychology, and propose a hypothesis to explain its presence in this data. I then consider how cognitive models converge on a similar explanation, and in the process contrast this interpretation with the currently extant interpretation of related work in terms of an interference effect. I close with consideration of implications of this effect for both pedagogical design and research practice.

A summary by Jane Jackson, Arizona State University:
Paul Camp observed U-shaped development of Newtonian reasoning in a middle school mechanics unit of 8 to 10 weeks (which followed 4 weeks of experimental design). All 3 of Newton's laws and related concepts (chiefly net force and acceleration) were introduced in the first 3/4 of the unit (which had 4 learning cycles of active learning, complex engineering design projects). "The unit is structured to make multiple passes through the same set of concepts in variable contexts, rather than continually adding new concepts in a linear sequence." (p. 11)

During those 8 to 10 weeks, "The iterative nature of the classroom activities, and the fact that they were making multiple passes through Newton's Laws, afforded periodic measurements of their understanding on a fixed set of concepts. These were made pre, post, and at the end of each cycle of activities. Thus, we were able to track the development of their understanding over time." (p.12) They used FCI and FMCE items and other multiple-choice, interviewed some students at length, observed entire classes, and gave small-group mini-challenges (similar to lab practicums).

He discusses the patterns of incorrect answers to questions on Newton's laws, net force, and acceleration (p. 27 to 32).

U-shaped development is an observation, not an explanation. It is a developmental trajectory that is observed in a vast and diverse range of concepts and abilities; thus he and some other researchers argue that it is a general feature of human cognition and learning (p. 34).

(p.34 & 35): U-shaped development "is so pervasive that some have been led to advocate a reorientation of the entire field of cognitive development along dynamic systems lines (Gershkoff-Stowe and Thelen 2004, Thelen and Smith 1994). Digital models of dynamic neural systems have naturally produced U-shaped developmental curves as the system attempts to maintain its current state in the face of incoming information from the environment, especially when said information exhibits strong patterns of coherent covariation (Elman et. al. 2001, Kelso 1995).

The key observation here is the existence of non-monotonic changes in performance during the learning of complex tasks. The key insight is that decrements as well as increments in such non-monotonic patterns in performance are byproducts of underlying monotonic improvements in memory and cognition. Competencies, once learned, do not disappear but they are unusually fragile while understanding reorganizes into a more mature form, and this fragility is reflected by variability in performance. But it is this internal structural and functional reorganization that characterizes cognitive development, not the sequence of states reflected in performance. Those are the outward manifestations of underlying dynamic processes."

He describes explanations for U-shaped development that others have given (p. 35-39), and then he suggests a hypothesis for U-shaped development in Newtonian reasoning, that he observed and documented (in mechanics in middle school). I quote him (p.39 & 40):

"I therefore conjecture the following model to account for the U-shaped performance data reported above. Initially, students have a largely phenomenological, and decidedly non-Newtonian, understanding in which very different rules apply in different situations and there is no global set of rules. The first result of instruction is the development of conceptual understanding, which appears to be the easier pedagogical problem to solve. The first peak in performance appears when that particular concept is an explicit target of current instruction, is forefront in the students' minds, and therefore easily accessible when they are asked relevant questions. It is indexed directly to the current classroom context, which in turn is the context of the quiz measuring performance. But as they move on from this initial burst of experience into other problems and different contexts, they must rely on remembering the correct Newtonian reasoning and recall is seriously complicated by the fact that their older phenomenological reasoning patterns are much, much better indexed and easily accessible than their newer Newtonian ones. They must experience failure of those memories and be reminded of what they have learned more recently. This representation or framing failure produces a decline in performance. If the class is successful, then continued experience with new contexts, coupled with representation failure and systematic reminding of the need for Newtonian explanations within those contexts, will in turn improve and broaden the indexing of Newtonian reasoning memories and lead to a second peak in performance. In short, framing resources develop more slowly than conceptual resources, and case-based reasoning provides a mechanism explaining why.

I quote from p. 42:
The hypothesis I advance, in which the Newtonian force "concept" is actually developmentally a composite entity containing a large number of interacting resources, some conceptual, some not, that all develop at their own rates along their own paths starts to make some sense of this data. One may accept that the FCI as a whole measures the Newtonian force concept, while understanding that the individual questions on the FCI measure various subsets of the resources embedded in that concept. Moreover, the individual questions, which divide the force concept the way a physicist would, do not always fall cleanly on well-defined resources from the developmental perspective but instead may require the coordination of several in order to answer the question. A high score on the FCI would then occur when all or almost all sets of resources are fully developed, but since individual questions rely on crosscutting sets of resources rather than individual, independent concepts, they may not exhibit consistently high performance until nearly the same point is reached.

He says (p. 44) that students must have multiple opportunities for REFLECTION; to create integrated knowledge, they must REVISIT and RECONSIDER ideas multiple times over an EXTENDED period in VARYING CONTEXTS [my caps]. "Wrestling with the issue of generalizing ideas from the specific context in which they were learned is part of integrating that instructed knowledge with experiential and other instructed prior knowledge."

[Jane's note in Sept. 2018: Learning gains persist for years, in interactive engagement physics courses in high school and college, as measured by the Force Concept Inventory. This indicates that the Force Concept Inventory is likely a good measure of learning mechanics if it is given at the end of the school year, after students have revisited the force concept in topics other than mechanics. A compilation on this phenomenon is at http://modeling.asu.edu/listserv2.html .]