MODELLING, STRATEGIC QUESTIONING AND THE LAWS OF STUDENT REASONING IN A-LEVEL MECHANICS

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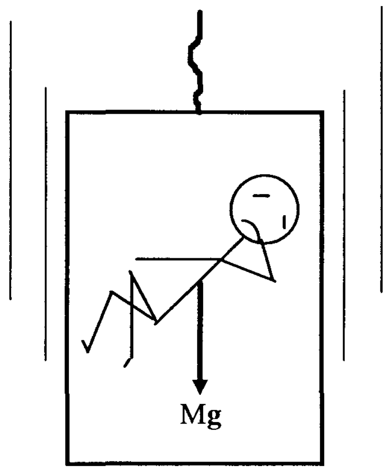
The Newtonian concept of force is a functional quantity that explains changes in motion - force as a relation between two bodies. Many A -level students, on the other hand, conceive force ontologicaliy - as a property that the body possesses. There is much research that suggests that these ontological beliefs are not acquired through experience of the physical world prior to learning mechanics, but may be formed when the student is asked to consider qualitative examples of force and motion for the first time. This paper reports on two possible laws of student reasoning in mechanics based on the results of a pilot-study.

INTRODUCTION

This paper is a continuation of the proceedings paper (Rowlands *et ai,* 1997) on the Socratic method as a teaching strategy that challenges 'misconceptions' and facilitates the construction of the Newtonian system within the students zone of proximal development, and reports on a study that suggests two laws of student reasoning in mechanics. 'Typifying the view of Vygotsky', Davydov (1988) argues that the method of (developmental) teaching should be based on its content - namely the logical structure of the subject being taught. Taking our cue from Vygotsky and Davydov, we begin with the logical structure of Newtonian mechanics.

LOOKING AT BOTH ENDS OF THE ZPD: THE STRUCTURE OF NEWTONIAN MECHANICS AT ONE END, AND THE NATURE OF INTUITIVE IDEAS AT THE OTHER

We do not experience force! What we do experience, however, are macroscopic objects interacting with macroscopic objects, including ourselves as macroscopic objects. When we see two objects colliding, we see the changes in motion as a result of the collision. What we don't see, however, is the force of interaction acting between the two objects. When we see a ball thrown into the air, what we see is its trajectory as a result of the gravitational pull of the earth (another object). What we don't see, or even experience, is the gravitational pull of the earth. If you are in freefall enclosed in a capsule of some kind, then you will experience the sensation of weightlessness, even though you are not weightless:



When you travel around a bend, you do not experience the centripetal force acting on you towards the centre of rotation. What you do experience, however, is the sensation of being pulled outwards (an experience of the imaginary 'centrifugal force'). If you were hit on the head with a hammer, and you momentarily experienced an arrow labelled 100 Ns, then that experience may be attributed as a form of concussion!

The point is that *force* in mechanics is not something we can experience. We experience the actions of other bodies, but *force* in mechanics is a concept, a functional quantity, that explains changes in motion due to the actions of other bodies. Force is not a property of an object, it is not a quantity that the object possesses. Rather, it is a relation between two bodies (either in contact, such as friction or normal reaction, or at a distance, such as gravity) and that relation is exactly specified by the laws of motion. The laws of motion are not empirical laws that can be discovered by measuring the variables in an experiment (a very important pedagogical point for those keen on an experimental or 'hands-on' approach. See Rowlands *et al,* 1999). They are not empirical generalisations such as 'all ravens are black', but express *transfactual tendencies* (Chalmers, 1982). In explaining the way in which physics speaks of the world, Chalmers (1982) states:

Let us take as an example Newton's first law of motion, the law that Alexander Koyre described as the explanation of the real by the impossible. Certainly no body has ever moved in a way that perfectly exemplifies that law. Nevertheless, if the law is correct, all bodies obey it, although they rarely get a chance to show it. The purpose of experimentation is to give them a chance to show it. If Newton's laws are 'true' they are always 'true'. They are not true only under experimentally controlled conditions. If that were so we would not be justified in applying them outside of experimental conditions. If Newton's laws are true they are always true, but are usually accompanied by the simultaneous action of other tendencies. If Newton's laws correspond to *anything it is to transfactual tendencies, which are very different from localised states of affairs such as cats being on mats* (p. 155).

The laws of motion are axioms and not empirical generalisations. They do not by themselves tell us anything factual about the objects of the world, but they do speak indirectly about the objects of the world by stating the precise way in which it is possible to describe the world by these means (Wittgenstein, 1961). The coherence of Newtonian mechanics consists in the way it accounts for all contingencies. The laws of motion define force in a way that stipulates how a phenomenon shall be treated by the system, and the system is unified in the sense that it can accommodate all accountable phenomena within the limitation of its domain (macroscopic objects with speeds that are not comparable with the speed of light). To quote Wittgenstein (1961):

Newtonian mechanics, for example, imposes a unified form on the description of the world .... Mechanics determines one form of description of the world by saying that all propositions used in the description of the world must be obtained in a given way from a given set of propositions - the axioms of mechanics. It thus supplies the bricks for building the edifice of science, and it says, 'any building that you want to erect, whatever it may be, must somehow be constructed with these bricks, and with these alone'. (Just as with the number-system we must be able to write down any number we wish, so with the system of mechanics we must be able to write down any propositions of physics that we wish) (proposition 6.341).
Mechanics is an attempt to construct according to a single plan all the true propositions that we needfor the description of the world (proposition 6.343, author's emphasis).

The way mechanics speaks of the world is unified, and the coherence of mechanics consists precisely in the way the system is a unified form of description. Student intuitive reasoning, on the other hand, lacks the coherence of the Newtonian system - it is not unified but fragmented (Rowlands *et aI,* in print). Newtonian mechanics is consistent in its account of different phenomenon, whereas student intuitive reasoning tends to lack consistency - it differs with respect to each phenomenon. Students may regard force and motion according to how they conceive the dominant features of the phenomena under investigation: the force acting on a car braking is in the opposite direction to the motion, yet the force acting on a ball thrown upwards has to be upward because the ball is going upwards. We do not experience force, but we do experience the motion of bodies, and our ideas of force are sometimes muddled with what we consider to be the dominant features of motion.

To understand mechanics in the way it describes the world, to explain phenomena qualitatively according to the Newtonian system, requires thinking in the abstract! With facilitation by the teacher, the class has to construct for itself the Newtonian system as a unified form of description - a sharp contrast to the fragmentary responses given by students as reported in much of the literature. To explain the world in accordance with mechanics as a unified form of description is to 'explain the real by the impossible' - that if objects were given a shove on a frictionless surface then they would move in unified motion, that the laws of motion would be invariant in a possible world of no gravity, etc. *ldealised abstraction* are the rules upon which we have to think in terms of mental models, and these rules are the laws of motion (Rowlands *et al*, 1999). Students may appear to have little difficulty in dealing with idealised examples that demand a quantitative response (e.g. *Calculate the acceleration of a particle down a frictionless plane inclined at 30° to the horizontal).* The real difficulties appear when students are asked to explain the world *qualitatively* within the constraints of idealised abstraction (e.g. *Two particles, one with a mass several times greater than the other, are released simultaneously from the top of an inclined plane. Which particle will reach the bottom first?).* Of course, the teacher can always set up the conditions that would reveal the answer. However, that would still leave the class to understand why both particles would reach the bottom at the same time.

The asking of concept and parallel questions presupposes a meaning that is only relevant to idealised abstraction. Each question is framed in a way that reveals the consistency of the Newtonian framework, but the raising of each question is determined by the responses to the previous question. The appropriation of meaning is structured within idealised abstraction, but the class is continually invited to construct that meaning as the students attempt to instantiate intuitive ideas to make sense of the phenomena as presented by the teacher. The teacher should not attempt to refer to these intuitive ideas as part of a 'scaffold' to facilitate a Newtonian understanding, but should raise anomalies that have the same explanation under the Newtonian system. In this way, Newtonian mechanics may be seen as a semiotic system - much more meaning is conveyed than is actually stated in the asking of concept questions, and cognitive strain will result as the student attempts to infer the meaning of the questions. 'Misconceptions' or 'alternative frameworks' may be considered as initial attempts to construct a meaning, and may be resilient to change given the cognitive strain in forming them. Concept questions may promote *cognitive conflict* (Graham & Berry, 1994), in the sense of the *gestalt-shift* from 'seeing that' (in terms of the intuitive ideas instantiated) to 'seeing as' (in terms of the Newtonian model).

CONCEPT QUESTIONS AS A DIAGNOSTIC TOOL AS WELL AS A TOOL OF REMEDIA TION - THE LAWS OF STUDENT REASONING IN A-LEVEL MECHANICS Force, as defined within the Newtonian system, is a relation between two bodies. Many students, however, conceive force ontologically - as a property that the body possesses (Nersessian, 1992). These ontological beliefs are not acquired through experience of the physical world prior to the learning of mechanics (force cannot be experienced), but may b~ formed when the class is asked to consider qualitative examples of force and motion for the first time. Conceptual changes of force and motion requires the construction of new concepts, together with the challenge to emerging intuitive beliefs, through strategic questioning. However, by challenging emerging intuitive beliefs we can reveal the laws of student reasoning in mechanics.

Similar to the 'experimental-developmental' method of Vygotsky *which calls for an experimenter to intervene in some developmental process in order to observe how such intervention changes it* (Wertsch, 1985), concept and parallel questions can be used to evoke responses so that we can analyse psychological processes that occur in mechanics instruction. In other words, within the zone of proximal development of a mechanics class, if we are to understand the cognitive abilities of the class as a *process* then we have to instigate that process by interaction with the class. The pilot-study with the HITECC (engineering foundation year) mechanics class, and informal intervals with sixth-formers, has suggested two laws of reasoning:

- Some students can develop their personal intuitive beliefs of force and motion with remarkable consistency and coherence (regression from the target concept), until an anomaly contradicts their ontological status of force .
- The greater the regression, the greater the cognitive conflict necessary.

Concept questions not only reveal the intuitive beliefs of the students, they can also arouse the students minds to life, sometimes with a remarkable coherence in their attempts to defend their beliefs. The three students from the Hitecc class pilot-study were able to respond consistently to the questions that were parallel to the concept question of the force acting on a vertically thrown ball:

Teacher. *But when I throw a ball and place my hand in my pocket... ..*
Student 1. *Yeah, but the force has comefrom you but is decreasing.*
Teacher. *It's decreasing?*
Student 1. *Yeah, as its losing velocity, its going to slow down and the force of gravity is going to be greater which is forcing it downwards.*
Teacher. *But if I am on a hull of a spaceship and I throw the ball, how is it going to go?*
Student 1. *It* is *going to go straight.*
Teacher. *But what is its motion like when it is going straight?*

Student 1. *Uniform.*
Teacher. *Is there aforce pushing it?*
Student 1. *Not after it has left you*
There appears to be a sigh of relief from the class.
Teacher. [looking at students 2 and 3, who seemed to have shared the same ideas as student 1] *So where is this force coming from then?*
Student 2. *Its own mass.*
Student 3. *l'd say it is from you, but decreasing.*
Class appears to be a little unsettled at this point.
[Student 2 appears to have a medieval impetus viewpoint, while student 3 appears to have an Aristotelian one. It was tempting to abandon the discussion since the whole class with the exception of the two students appeared to have grasped the point. However, this may have been a consensus within the class to 'keep me happy' so as to move on. Moving on was a temptation because subsequent concept-questions could always be related to the previous phenomena considered. Nevertheless, I had attempted to 'crack this nut' as it might have revealed a successful strategy].
Teacher. *But why is the force from me, from the hull of the spaceship* ....
Student 3. *There is no resistance ...*
Student 2. *Oh, I know, its the force stored in the mass.*
Teacher. *Force stored in the mass? In fact that is quite often given, even by Aristotle* [a mistake, I should have said the medieval impetus school]. *Aristotle argued that force is a property of the object.*
Student 2. *The force given by the thrower goes into the ball - into the mass - and in that situation, stored in the mass, and because nothing is stopping it - it is in a vacuum - it just carries on. But if another force is applied to it, it will change direction* [hand gesture of a projectile's trajectory]. Student 4. [who has been waiting a long time to respond]. *The only force acting on a thrown ball is gravity. If a ball is in uniform motion then no force is acting on it.*
Student 5. *The force is gone.*

Students 2 and 3 had set themselves apart from the rest of the class, the majority of which appeared to have little difficulty in giving a Newtonian response to the original concept question. Subsequently, the three students became very consistent (and entrenched) in their arguments. For example:

- *If there is no such force* [pushing a projectile] *then why does it go to the top of the arc before gravity takes over?*
- *If a ball hits a wall, then the dent in the wall is caused by the force in the ball.*
- *There is a force opposing the motion of the car braking, namely friction; but the force pushing the car gradually weakens - and that is why the car slows down until it stops. When the car stops, the frictional force and the push are in equilibrium.*

I raised the example of the ball held between two fingers on a train travelling in uniform motion and asked what was the speed of the ball relative to a stationary observer and if there were any horizontal forces acting on the ball. There were facial expressions of cognitive conflict from students 2 and 3. I had raised the question almost by accident, as I had just remembered the example raised by Gallileo of the sailor in the crows nest who drops a ball - does the ball land in front of the mast, at the foot of the mast or behind the mast? Throughout the rest of the course the two students were able to provide a Newtonian account of complicated qualitative models.

No one has observed or experienced uniform motion in the total absence of force; nonetheless, the anomaly of the ball in the train is the closest that one can consider uniform motion in the absence of force. I was able to formalise the first law of motion and to move the class collectively from the idea of uniform motion in the absence of force to uniform motion in the absence of a net (resultant) force:

Horizontal uniform mition requires no force

Horizontal uniform motion and horizontal forces ~ net horizontal force = 0

In the above discussions, the students were becoming more and more consistent in their developing argument that force is a property of the object and that this force is given to the object by an agent (a thrower). Their developing argument had assimilated each parallel question according to the original notion that a thrown ball moves up because the force required to overcome gravity is the force that was given by the thrower. However, there appeared to be expressions of cognitive conflict on the faces of two students when the anomaly of the ball on the train was asked. Subsequent informal one-to-one interviews with a dozen pre-instructed sixth-formers suggests that if this question is asked after a series of related parallel questions, then cognitive conflict will occur (perplexed facial expressions, minutes of silence, fidgeting). On one occasion a student refused to see the relevance of the question after giving the correct answer. Once cognitive conflict occurred it appeared relatively easy to prompt the student to explain why a vertically thrown ball slows down. However, on three occasions I had given the ball on train question first. In each case the question was answered correctly (with no apparent cognitive conflict), but subsequent parallel questions were answered incorrectly. This suggests that the ball on train question has an 'impact' only if the question is asked after a series of parallel questions. It seems as though the question cannot sustain a developing 'force is the property of the object' argument. In other words, the answer to the question undermines the belief that the ball has to have a force in order to maintain uniform motion.

We are now involved in a research project that includes clinical interviews that would hopefully verify the two laws of reasoning in mechanics: *The more parallel questions that can be 'assimilated', the greater the entrenchment and hence the greater the need to induce cognitive conflict. Cognitive conflict can occur if a question undermines the students ontological status of* *force*. If these two laws are verified, then the next stage of the project will be the consideration of the laws in a classroom situation.

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