Mental Models of Force and Motion in 11 to 18 Year Olds.

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Abstract

Previous studies have suggested that students may compartmentalise knowledge: their everyday intuitions will serve in everyday contexts and their academic knowledge is activated, if ever, in academic contexts. In this study we put forward a case where significant numbers of students of Newtonian theory provide mixed explanations of motion in the same context. They typically switch from one model to another depending on the values of the masses and forces involved.

Introduction and Background Literature

Science students are often faced with a dichotomy between their existing knowledge or beliefs and the new knowledge, and many students' intuitive models of force and motion are at variance with scientific theory. The Aristotelian model has been observed in students in schools and universities in many countries (Viennot, 1979, Helm, 1980, Watts et aI, 1981, Sjoberg and Lie, 1981,Osborne 1991). Misconceptions can be very resistant to instruction (Fiengold et aI, 1991, Ebison, 1993), and there is some evidence that the proportion of the students holding some misconceptions can increase after instructi on (Roper, 1985).

West and Pines (1986) discuss the situation where the intuitive knowledge is well established, and the academic knowledge conflicts with this belief system. They note that the pupil must exchange one concept for the other to resolve the conflict, and proposed three possible outcomes of instruction:

- *conceptual exchange,* where the subject shifts to the new belief system;
- *compartmentalization,* where the new knowledge and old belief systems coexist;
- *no learning,* where the subject simply retains the old beliefs.

Berry and Graham (1991) propose a similar model of learning, but have different categories of compartmentalization.

Where the two models coexist, it has been suggested that the taught model is usually favoured for the academic questions, but the intuitive model for the "real world" problems (Gunstone and Watts 1985, Berry and Graham, 1991, Graham and Berry, 1993, Swartz, 1995).

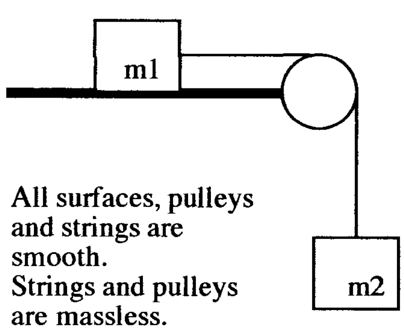

Figure 1 The Two Mass Problem.

We describe an investigation into secondary school children's mental models of force and motion. Pupils face a major conflict between their naive mental model, and the

Phases exhibited	P01	P012	P02	P2
Year 8	8	5	7	0
Year 11	2	0	6	0
Year 12 &13	1	5	0	6
Totals	11	10	13	6
			N =	40

Table 1 Interview Results.

Newtonian model. Experience in the classroom, and initial investigations with Year 12 and 13 students (Mildenhall, 1995, 1998) indicated that compartmentalization may be quite common, leading to transitional stages of learning when the subject holds both Aristotelian and Newtonian models at the same time. A discontinuous model, where the nature of the motion changed as the magnitude of the motive force increased, was identified. There could be three phases of motion: *Phase* 0, when the force was not large enough to cause motion; *Phase 1,* when the system moved at a constant speed; *Phase* 2, when the system accelerates.

The initial investigations also identified two other commonly held beliefs: the *height intuition* where the subject believes that the gravitational force increases significantly with height; and the *balance intuition,* where the subject believes that a mass - pulley system is in equilibrium if the sums of the masses about some arbitrary point are equal.

Interviews

We interviewed 20 pupils from Year 8, and 8 pupils from Year 11. Year 8 pupils were interviewed for two reasons: to explore the model with which the children started at secondary school (the *base intuitive model);* and so that they could be reinterviewed before they were taught Newton's laws formally if necessary. Year 11 pupils were used to assess if the mental models changed during GCSE instruction. The choice of subjects was pragmatic: they attended my school, and most were in my mathematics set. The school is selective and so the subjects are from the higher ability range.

The interviews were structured by presenting the subject with a number of cards showing different Two Mass Problems (figure 1), where the ratio ml:m2 varied. In the problems all surfaces and pulleys were friction free, and the strings and pulleys massless, and the string inextensible. Subjects were briefed on these conditions before the interview; the briefing recognised that the conditions were not practical, but that was how the subject was to imagine the system shown on the card. Subjects were asked to sort the shuffled cards according to the motion of the system when it was released from rest. The interview was recorded (audio only) and the tapes transcribed verbatim for subsequent analysis.

The results of the interviews are summarised in table 1, where the phases exhibited are shown as P012, etc. in the obvious way. The main points are:

- The base intuitive model is the two phase model consisting of the static and the constant velocity phases only, and it is very similar to the model Aristotle describes in his physics.
- The balance and height intuitions are common.

- The subjects' had problems with abstraction. They did not realise the full implications of the friction free conditions postulated, and they constantly worried about "concrete" features - the table mass running into the pulley, the hanging mass hitting the floor, and so on.
- The subjects' understanding offorce and motion is handicapped by their lack of understanding of the nature of weight, of vectors and the way that vectors combine.

Questionnaire

The data from the interviews were used to design a questionnaire. The questionnaire divided conceptually into two parts: the Model Identification Part; and the Feature Identification Part. The Model Identification Part identified the subject's Mental Model in terms of the phases of motion involved, with the Two Mass Problem, with 1 kg resting on the table. The hanging mass in the first question was 0.1 kg, and the hanging mass for the next question was increased or decreased depending on the answers until a phase change was evident. If an acceleration phase was detected, a later question checked whether the subject was arguing from Newton's Laws, or from the Height Intuition.

The Feature Identification Part, investigated the force required to cause a phase change in the motion, the form of the laws of motion for the moving phases, the reason for the static phase, and whether the subject was arguing form the Height Intuition. Most of the features were checked with variants of the problem in which the hanging mass is replaced by a scale pan. For example the phase change point and laws of motion were investigated by asking how much sand (within certain bands) would have to be put in the scale pan to cause motion of the appropriate type. This was followed by questions asking how much sand would be needed to double the motion, and questions about the nature ofthe motion. The questionnaire was validated by comparing the results with the results of interviews. and reliability checked using a test - retest technique (Mildenhall, 1998).

Model	P01	P012	P02	P1	P12	P2	P0
No Inst	30.8	20.6	9.8	16.5	6.2	6.7	9.5
With Int	28.8	18.1	8.8	17.7	5.0	15.8	5.8
Overall	30.0	19.6	9.4	16.9	5.7	10.3	8.0

(Percentages of row totals.)

Table 2 Questionnaire Results

The questionnaire was completed by 649 A -level mathematics students in the Manchester area. They were drawn from Sixth Form Colleges, and independent single sex grammar schools. The results from the model selection part are shown in table 2. Analysis revealed:

- The main personal attributes which predict whether a subject will use the Newtonian Model consistently in the questionnaire are:
  I. if they have been taught Newton's Laws;
  2.their ability, (indicated by GCSEMathematics grade); 3.
  if they are being taught A - level Physics.
- Overall 30.8% of the sample started their A - level studies with the Base Intuitive Model, and 28.8% still held that model after instruction. Proportion of physicists and non physicists holding the Base Intuitive Model before instruction is similar (30.1 % and 31.4%

respectively), but 19.8% for Physicists after instruction, and 35.1 % for others.

- The Newtonian Model is exhibited by only 6.7% of the subjects before instruction and 15.8% after instruction. (Physicists 12.3% and 28.3%, others 2.7% and 7.1 %).
- The Balance (59%) and Height Intuitions (63%) are very common in all the groups.

Discussion

We believe that the observed behaviour can be explained by the cognitive structure shown in figure 2. This structure has three main parts:

1. an intuitive mental model;
2. an academic mental model;
3. a model selection mechanism.

The *intuitive mental model* is the subjects' mental model built up from many years experience of moving things in the real world, starting from their earliest years. Based as it is on their common sense interpretation of what they observe around them, this model owes more to Aristotle than Newton. This is to be anticipated. Friction is a fact of real life, and experience tells you that you must keep pushing something to keep it moving. Stop pushing and the thing stops. It is "common knowledge" that you would have to push twice as hard to make the object move twice as fast, and "obvious" that you would have to push a heavier object harder than a light one to make it move; in fact if the thing is heavy enough you may not be able to move it at all. The Newtonian explanation for this phenomenon is friction of course, but the mental leap required to appreciate this fact is not at all trivial. To do this successfully we must be capable of quite abstract thought, because the condition we are now postulating, complete freedom from friction, is outside our normal experiences.

We have called the second model the subject may hold the *academic model.* This model represents the subjects' understanding of the formal instruction in mechanics they have received. Before the subject has received any formal instruction in mechanics they will not hold an academic model at all.

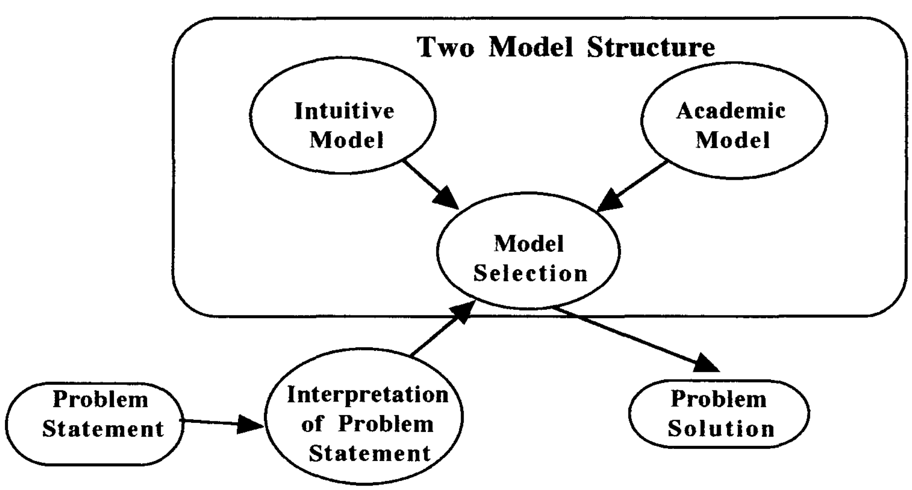

Figure 2 The Two Model Structure in Action

When faced with a problem, the subject uses one of their mental models as a framework on which to build their solution. They perceive certain clues in the problem statement to select either their intuitive or their academic mental model. There does seem to be a tendency to use the intuitive model when faced with a qualitative "real world" problem. For example if the subjects are asked about the force needed to push a car, they "know" that they must apply a force of some magnitude before the car will move. On the other hand the need for equations and calculations steers the subjects to the academic model for a quantitative question. However this is not necessarily the case: in this research we see subjects acting intuitively to what is essentially an academic question. In some cases the intuitive model may suggest to the subjects that the quantitative problem does not make sense. For example they might be asked to find the movement of something that the intuitive model says will remain stationary. If the academic model does not exist then the selection mechanism defaults to the intuitive model. There is a transitional state where the intuitive model is selected until the force is above some magnitude, and so P012 will be exhibited, if the subject holds the base intuitive model.

We believe that the learning process is iterative, and the subjects can go through more than one cycle of modifications to their intuitive models. The interviews revealed that the students start their A -level mechanics studies with the two phase model POI. This model has two main features, the reluctance (static) phase and the Aristotelian (constant velocity) phase, and instruction can suppress either of these phases.

We believe the findings can be used in the classroom in the same way as Berry and Graham's (1991) concept questions. First we must find out if there is evidence that the pupil holds a mixed model by asking qualitative questions such as the Two Mass problem with various motive forces. We now have the value of the hanging mass which the pupil believes will cause motion, and we can expose the contradiction implied by this when the conditions are friction free. However we should not be too optimistic that we will bring about concept exchange, because the intuitive model has served the students very well for a great number of years. Indeed it continues to serve them well in their daily interactions with the inanimate objects around them. A more realistic aim is to ensure that they are aware that they do hold these two models, and know when to use each one.

Conclusions

Most children start their Newtonian mechanics instruction with well established intuitive models of force and motion. This is the Aristotelian model: the force has to be big enough before motion can take place, and when the force is big enough it causes motion, not change in motion. They face a major clash between this model and the Newtonian model being taught, and compartmentalization is a common outcome of initial instruction in Newtonian mechanics. However the result is more complicated than the literature suggests. Students do not reserve their academic model for academic questions and their intuitive model for 'real world' questions, but use certain features in the problem statement to decide which model to use. One of the features appears to be the relative magnitudes of the weight of the mass being moved and the motive force. Detailed knowledge of a students mental model of force and motion does give the opportunity to challenge the model by discussing the contradictions inherent in the model

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