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A Psychological Process Model of the Solution of Mechanics Problems by Elementary School Students: An Interdisciplinary Project

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Abstract

The purpose of this study is to propose a process model to explain elementary school students' solutions of three simple problems in elementary mechanics. Forty eight 5th grade students were given three drawings depicting objects of various sizes in different kinetic states or being pushed by a human agent. They were asked to say whether a force was being exerted on the objects and to explain why. A process model has been proposed to explain students' answers to the three questions. The innovation of the process model is that it attempts to link two levels of representation: A *semantic level*, where a concept is analysed in terms of the presuppositions, beliefs, and mental models that underlie it and a *syntactic level* that specifies how concepts are related to other concepts in hierarchical categories. The work has been validated by a computer model designed by the AI team (Vosniadou, Kayser, Champesme, Ioannides & Dimitrakopoulou, in press).

1. Introduction

The present project is based on collaborative and interdisciplinary work that took place in the framework of the project *Learning in Humans and Machines* sponsored by the European Science Foundation. The purpose of the research was to bring together the know-how from the fields of cognitive psychology and artificial intelligence in view of the fulfillment of two main goals. The first, mostly relevant for cognitive psychology, is to propose a theory of the development of knowledge acquisition in mechanics, with the help of computational models, clearly formalised and precisely testable. The second, relevant mostly for artificial intelligence, is to obtain powerful guidelines for a more effective design strategy of learning systems, starting from the very basic issue of what knowledge they should handle and how to represent it.

2. Theoretical Framework

2.1 Mental Models of Force

There are different ways to think about the way concepts are organized in the knowledge base. Some researchers pay particular attention to specifying assumed hierarchical relations among concepts and categories, in other words to providing a *syntactic description* of conceptual organization. Other researchers pay more attention to mental representations or mental models (e.g., Larkin, 1983), or to assumed underlying theoretical structures, such as schemes or theories (Carey, 1991).

In previous work (Ioannides and Vosniadou, 1995; submitted) we used the theoretical model and methodology described in a series of studies on knowledge acquisition in astronomy (Vosniadou and Brewer, 1992; 1995; Vosniadou, 1994), to investigate the development of the concept of force. The results showed that it is possible to classify approximately 80% of the students in our sample as using one out of six relatively well-defined mental models of force in a logically consistent way. More specifically, the six mental models of force shown in table 1 were identified. These models were used in different frequencies by students ranging in age from 5 years (kindergarten) to 15 years (9th grade).

As can be seen in table 1, young children start with a mental model of force as an internal property of objects that appear to be large and/or heavy. Soon, the notion of an *acquired force* is added to or replaces the notion of *internal force*. This acquired force is supposed to be imparted to a moving inanimate object by the push or pull of another object and to explain the object's movement. The use of force to explain the movement of inanimate objects has been noted in previous research (Clement, 1983; McCloskey, 1983). Older children start to mention the force of gravity but construct various misrepresentations of gravity which will not be discussed here (for more details, see Ioannides and Vosniadou, 1993).

2.2 Hypothesized conceptual structure

Mental models are assumed to be based on the subject's interpretation of the incoming information and to be constrained by underlying knowledge structures. In the theoretical framework we have developed to explain the process of acquiring knowledge about the physical world, we have made a distinction between what we call *specific theories* and *framework theories* (Vosniadou, 1994).

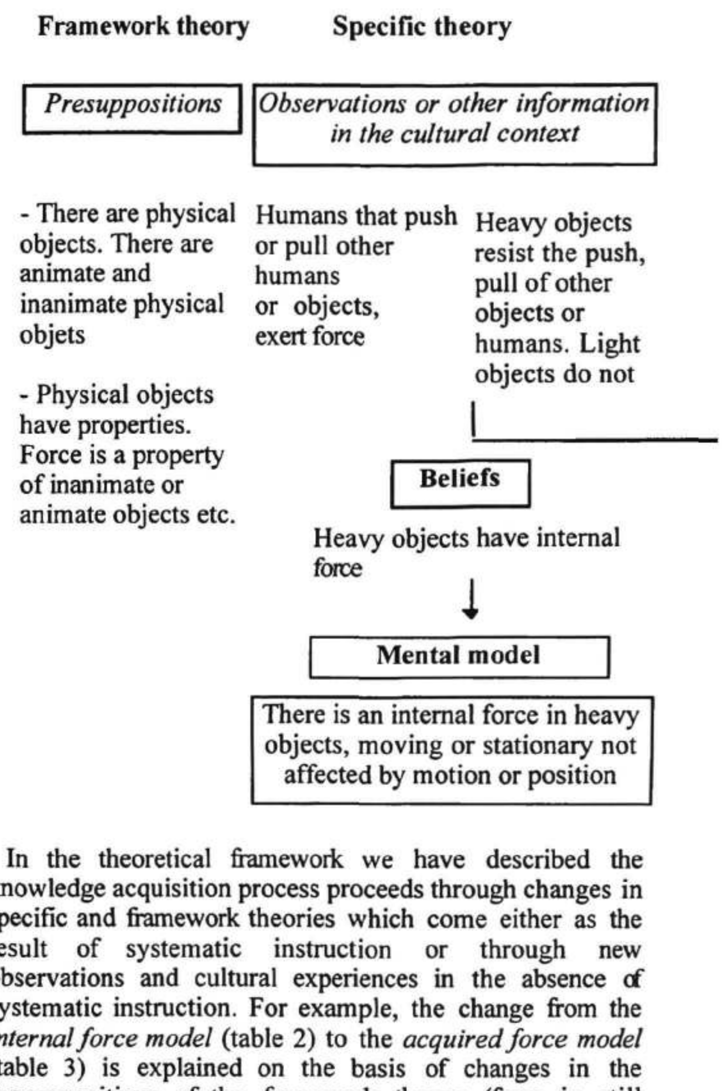
Table 1: Mental models of force and their use as a function of grade

Mental Models	Kind/ ten	4th grade	6th grade	9th grade
1. INTERNAL FORCE: There is an internal force in heavy objects, not affected by position or motion	40%	6.7%	0%	0%
2. INTERNAL + ACQUIRED FORCE: There is an internal force in heavy objects that are stationary and an additional, acquired force, when they move.	13.3%	26.7%	13.3%	0%
3. INTERNAL FORCE IN STATIONARY OBJECTS: There is an internal force only in stationary, heavy objects.	13.3%	6.7%	0%	0%
4. ACQUIRED FORCE There is an acquired force in moving objects only.	0%	10%	43.3%	20.7%
5.GRAVITY+ ACQUIRED FORCE: There is the force of gravity on all stationary and falling objects, and an acquired force in all objects that have been thrown.	0%	6.7%	6.7%	46.7%
6. NO FORCE: There is no force on any object unless an obvious agent is acting on it	0%	0%	0%	3%
7. Other	6.7%	10%	13.3%	6.7%
8. Mixed	26.7%	33.3%	23.3%	23.3%

A framework theory is supposed to consist of certain fundamental presuppositions about the way physical objects behave, acquired early in infancy. Specific theories consist of a set of interrelated propositions or beliefs that explain physical phenomena, generated through the interpretations of observations and information presented by the culture under the constraining influence of the relevant framework theory. In tables 2 and 3 we can see the assumed framework and specific theories that underlie the *model of internal force* and the *model of acquired force*.

As can be seen in table 2, *the internal force model* is assumed to be constrained by an underlying presupposition that force is an internal property of physical objects. The specific theory underlying this mental model of force appears to be based on the everyday observation that heavy objects resist the push/pull of other objects or humans.

Table 2: Hypothesised conceptual structure underlying the *internal force model*



In the theoretical framework we have described the knowledge acquisition process proceeds through changes in specific and framework theories which come either as the result of systematic instruction or through new observations and cultural experiences in the absence of systematic instruction. For example, the change from the *internal force model* (table 2) to the *acquired force model* (table 3) is explained on the basis of changes in the presuppositions of the framework theory (force is still considered to be an internal property of animate objects but not of inanimate objects). There are also changes in the beliefs of the specific theory that take place. As table 3 shows, inanimate objects are differentiated from animate objects on the grounds that they lack self-initiated movement. Force is now considered to be the cause of an inanimate object's motion. In this theoretical framework, concepts are analyzed in terms of the assumed theoretical structures that underlie them. Conceptual change is explained in terms of changes in the presuppositions and beliefs that may come spontaneously or as the product of instruction.

Table 3: Hypothesised conceptual structure underlying the *acquired force model*

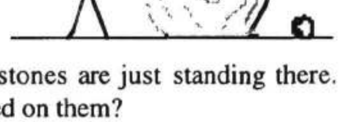
Framework theory	Specific theory		
Presuppositions	*Observations or other information in the cultural context*		
Ontological - There are physical objects. There are animate and inanimate objects -Physical objects have properties. Force is a property of animate objects -Physical objects are in rest or in motion etc.	Inanimate objects need to be pushed or pulled in order to be moved	Animate objects move by themselves	The motion of an inanimate object continues for a while and then it stops
	Beliefs		
Epistemological - In inanimate objects, processes, like motion, need to be explained - Explanations should be causal etc.	When an agent pushes/pulls/throws etc. an object he/she imparts to the object a force which sustains its movement	The object stops when the force disappears - goes away	
	Mental model		
	There is an acquired force in inanimate moving objects		

3. Process Model

3.1 Force in animate objects

In the present work we tried to use the theoretical framework described above as the basis for a process model to explain 5th grade students' responses to problems in mechanics. Let us start with question 1, which appears in table 4.

Table 4: Question 1



These two stones are just standing there. Is there a force exerted on them?

We hypothesized that in order to answer this question, students would search their knowledge base for information regarding force. If they would form the internal force model, they would give responses of the kind *Yes, there is a force exerted on the stones because they have weight, or mass*, or *There is force exerted on the first stone because it is bigger or heavier than the smaller stone.* In the case students formed the acquired force model, we expected answers such as *No, there is no force exerted on the stones because they do not move.* The response types we actually obtained when we gave this question to 5th grade students are shown in table 5.

Table 5: Students' responses to question 1

	Response types	Assumed mental model	%
1.	Yes, a force is exerted on both stones because they are big/heavy they have weight/force	Internal force	18.4%
2.	No force is exerted on the stones because they are not moving	Acquired force	26.5%
3.	Yes, a force is exerted on both stones because the earth pulls/attracts them	Force of gravity	20.3%
4.	No force is exerted on the stones, because the man does not push them/exerts effort	Push/pull	30.6%
6.	Other		4.2%

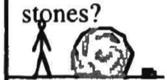
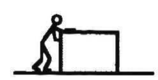
As we can see a large percentage of the responses (45%) to question 1 can be explained by assuming that students used either the *internal force model* (18.4%), or the *acquired force model* (26.5%), or the *force of gravity model* (20.3%). This leaves unexplained the remaining 34.8% of the students' responses. Some children gave responses of the sort *No force is exerted on the stones because the man does not push them, or exerts effort.* These responses indicated that some students did not focus their attention on the inanimate objects (the stones) but the animate object (the man) and noted the absence of force being exerted on the stones by the man.

After a close examination of students' responses to question 1 as well as to questions 2 and 3 (shown in table 6) we added another mental model of force, the *push/pull model.* This model had been identified in our previous work in reference to animate objects. It attempts to capture the notion of force associated with animate rather than with inanimate objects. According to this model, force is a property of animate objects that can act on other objects (mainly through push or pull). It is related to physical characteristics of objects such as size and weight, and it transfers to other objects by direct contact. Using this additional model of force we were able to account for about 95% of students' responses to the three questions.

3.2 Context effects

We have argued that 5th grade students' responses to the three questions about mechanics problems shown bellow can be explained by assuming that these students construct one of four relatively well defined mental models of force. It appears, however, that these mental models are not mutually exclusive and that the probability of activating one model of force as opposed to another is influenced by the verbal and pictorial content of the questions asked. Table 6 shows the percentage of responses obtained for the four models of force.

Table 6: Context effects: Percentage of responses as a function of question type

Mental Models of Force	Question 1: The two stones are just standing there. Is there a force exerted on the stones? 	Question 2: The second stone moves, the first does not. Is there a force exerted on the stones? 	Question 3: The man cannot move the box. Is there a force exerted on the box? 
Push/pull	30.6%	61.2%	89.6%
Internal	18.4%	8.1%	0%
Acquired	26.5%	24.4%	4%
Gravity	20.3%	0%	2%

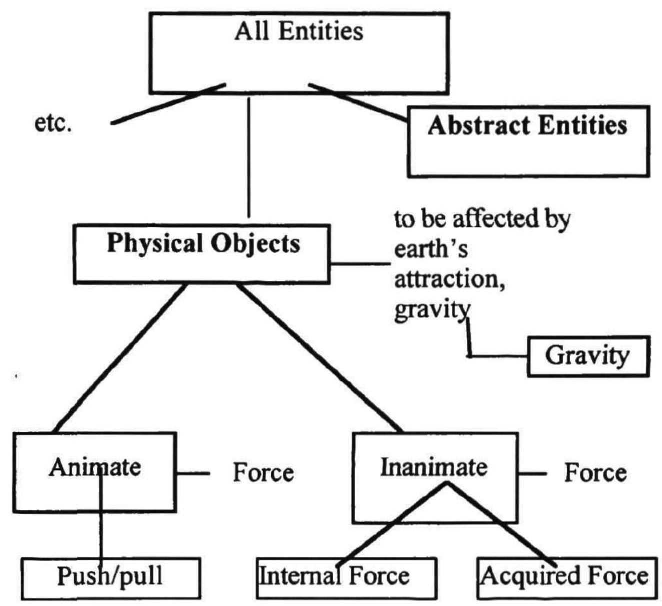
1. The push/pull model is the most frequently used. Its probability of use increases in the presence of an animate agent exerting force on an object (Questions 2 & 3).
2. The gravity model is the least frequent. Its probability of use increases in the absence of a push/pull by an animate agent (Question 1).
3. The internal and acquired force models are also most frequent in the absence of a push/pull by a human agent. The internal force model was most frequent in the absence of movement (Question 1).

3.3 Internal Consistency

The context effects described above indicate that each student has at his/her disposal different alternative representations of force which are activated selectively in different contexts. As we saw, there are noticeable changes in the frequency of use of the four models of force in the different questions by the same subject population. We also know that the different mental models of force must be relatively unconnected from each other and not integrated in a higher order system. This must be the case because we found students to use only one model of force at a time. In other words, we did not have even one case of a student who used more than one model to answer a given question. We did not have responses of the sort, *Yes there are two forces exerted on the stone. The force of gravity and the force from the man's push.* From this we deduce that the different models of force are relatively isolated from each other and not integrated in a higher order system.

The co-existence of more than one mental models of force raises the issue of internal consistency. So far we have argued in our work (Vosniadou, 1994; Vosniadou & Brewer, 1992, 1994) that most students are logically consistent in their use of not more than one mental model to answer our questions about the earth, the day/night cycle or about force. Are the present findings contradicting our previous claims?

Table 7: Assumed Categorization of the Concept of Force (for elementary school children)



We believe that the problem can be solved if we assume that the *internal force* and *acquired force models* apply to inanimate objects and that the *push/pull model* applies to animate objects, as shown in table 7. In other words, we assume that in the conceptual system of the 11 year old child, force is categorized differently for animate versus inanimate objects. For animate objects, the push/pull model of force applies, whereas for inanimate objects we have the models of internal and acquired force (in addition to the other models mentioned in table 1). In such a system, internal inconsistency appears only if the internal and acquired force models are used by the same child in different contexts. An examination of the data shows that out of a total of 49 subjects, only one subject used the internal and acquired force models inconsistently (the internal force model in questions 1 and 2 and the acquired force model in question 3).

This still leaves unsolved the problem of how the mental *model of the force of gravity* is used. It appears that the gravity model comes through instruction to be added to the existing conceptual system of the 11 year old child and to be interpreted to apply to physical objects in general. Thus, the gravity mental model can theoretically take the place of any animate or inanimate model of force. When contextual cues lead to the activation of the gravity model, the search stops there and the other mental models of force are not utilized. We understand that this is a very preliminary treatment of the notion of gravity. We know from previous work that there are various misconceptions of gravity. These issues are further investigated in ongoing work.

To conclude, as shown in table 7, *force* can appear in different places in an assumed categorization tree. It can appear under inanimate objects either as an inherent internal property *(internal force)* or as an acquired property *(acquired force)*. It can appear under animate objects as the force exerted by a person's *push or pull*. Finally it may appear as a property of physical objects to be affected by the earth's attraction *(gravity)*. On the basis of our previous developmental work in this area we can say that these categorizations of force appear to have evolved from a simpler system where the notion of gravity was absent and were the internal force model preceded that of the acquired force. Not much is known about the models of force associated to an animate agent.

4. Validation

From an A.I. point of view, the task of providing a model adapted to the above findings appears very difficult. As a matter of fact, the problem requires the presence of several "copies" of the same concept, e.g. *force*, within a single global representation. Details on the solution adopted are given in [Vosniadou & al., in press]. Briefly, each fact and rule of the knowledge base is indexed with a boolean vector indicating in which model(s) — e.g. *Internal Force* (IF) and *Acquired Force* (AF) — it is considered as valid. Facts and rules are provided in a language exactly tailored for the needs of this experiment, which can be seen as a syntactic variant of a fragment of first-order predicate logic. A very brief description of the model IF is given below:

```
inanimate: is a physical object
           relation weight (≤ 1): a measure
           relation force (≤ 1): a measure
Inference rule IF.1:
  for x: an inanimate
  if is a(weight of x, measure)
  then x with force: weight of x
```

This means that, in this model, inanimate objects may have weight and (internal) force, and that if students have a (qualitative) measure of the weight of an object, say big, then they infer that its internal force is also big. In contrast, in the model AF, we find the following (somehow simplified for keeping explanations clear):

```
inanimate: is a physical object
           relation acquired force (≤1): a measure
Inference rule AF.1:
  for x: a move
  if is a(cause, push)
  then term of x with acquired force: intensity of cause of x
```

Here, inanimate objects may have acquired force, and if students know about a move caused by a pushing event, they will infer the existence of an acquired force for the moving object (the role term connects an event and the object it concerns, therefore x being the move event, the moving object is accessed through the name term of x), and its qualitative value will depend on how strong the push has been (intensity of cause of x).

In order to validate this representation, we have implemented the language and checked that, when the description of a situation was given to the model, the inferred features were exactly those that could be expected from a student supposed to use that model.

Example: we describe here partially how the question: *The same man pushes two stones. The small stone moves, the big one does not. Is there a force exerted on the stones?*, is translated in our representation:

```
man: an animate
bigStone: an inanimate
          with weight: bigValue
manPush: a push
          with term: man
          with theme: bigStone
          with purpose: movingIntention
movingIntention: a move
                 with term: bigStone
                 with new-state: intendedState
intendedState: a moving
               with term: bigStone
```

First, the physical entities are asserted e.g., a man and a stone with big weight (we deal here with qualitative values of weight). Next, the push is described by means of its agent: the man, its object: the big stone and its purpose which in turn is described as an attempt to change the state of the stone, namely getting it moving.
Now if we run the model with these data, we get:

```
** manPush with transferred: big
```

i.e., we infer from the purpose of moving a big object that the qualitative intensity of the push is big. Then we get:

```
** assert newforce-exerted.1
        with term: bigStone
        with cause: manPush
        with intensity: big
```

i.e., we infer the existence of an exerted force on the big stone, with some of its attributes. Concerning the small stone, as manPush succeeds, the rules that applied above do not fire any more, and no force exerted is created.

The results obtained here are in complete agreement with the expected answers of a subject using the model.

5. Summary and Conclusions

It appears that in the conceptual system of an 11 year old student, *force* can have different representations that are categorized in different places, e.g., as a property of inanimate objects, as the force of gravity, as something that requires push or pull by an animate agent, etc. These alternative representations of force become available as information comes through observation and from the culture in the form of systematic or unsystematic instruction. In previous work we described some of the beliefs and presuppositions about force that underlie these representations. In the present work we note that the different representations of force are associated with different contexts of use. Depending on the nature of the question and on the context, the student activates selected pieces of his or her prior knowledge to eventually create a specific mental representation of force on the basis of which he or she provides a response. On the basis of the present evidence, it appears that for most 11 year olds the different meanings of force are isolated and have not been integrated into a higher order system. Finally, the meaning of force as an abstract entity has not yet appeared.

We believe that this work succeeds in capturing important aspects of the concept of force in young children, both in terms of how it is related to assumed underlying beliefs and presuppositions (semantic description) and in terms of its relationship to other concepts and categories (syntactic description). It also provides a rich basis for understanding the process of conceptual change, which will be described in future work.

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