

# Introducing mechanics by tapping core causal knowledge\*

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## Abstract

This article concerns an outline of an introductory mechanics course. It is based on the argument that various uses of the concept of force (e.g. from Kepler, Newton and everyday life) share an explanatory strategy based on core causal knowledge. The strategy consists of (a) the idea that a force causes a deviation from how an object would move of its own accord (i.e. its *force-free* motion), and (b) an incentive to search, where the motion deviates from the assumed force-free motion, for recurring configurations with which such deviations can be correlated (*interaction theory*). Various assumptions can be made concerning both the force-free motion and the interaction theory, thus giving rise to a variety of specific explanations. Kepler's semi-implicit intuition about the force-free motion is *rest*, Newton's explicit assumption is *uniform rectilinear motion*, while in everyday explanations a diversity of pragmatic suggestions can be recognized. The idea is that the explanatory strategy, once made explicit by drawing on students' intuitive causal knowledge, can be made to function for students as an advance organizer, in the sense of a general scheme that they recognize but do not yet know how to detail for scientific purposes.

## Introduction

This article concerns a new approach for introducing mechanics at secondary level, based on the idea of providing students with a *content-based outlook* on what they are going to learn and why (Lijnse and Klaassen 2004):

- (a) *new knowledge* should fit in with *existing knowledge*,
- (b) students should be *motivated* to extend their knowledge in a given direction.

\* A previous version of this article was presented at the 2006 GIREP Conference.

Our claim furthermore is that everyday and scientific explanations of motion have the same structure based in core causal knowledge, the differences being essentially due to differences in interest. We argue that this basic causal explanatory structure, which we claim the students have at their disposal (*existing knowledge*, at least implicitly), can be made to function as an explicit directive guide—a kind of advance organizer (Ausubel 1968). For students learning the scientific explanation of motion (*new knowledge*), this would provide a content-based outlook on what they are going to learn and why (*motivation*).



**Figure 1.** Causes produce deviations from how things would carry on of their own accord.

### The basic structure of explanation of motion

In this section the claims made above are described in more detail in relation to our study (see also Klaassen 2005).

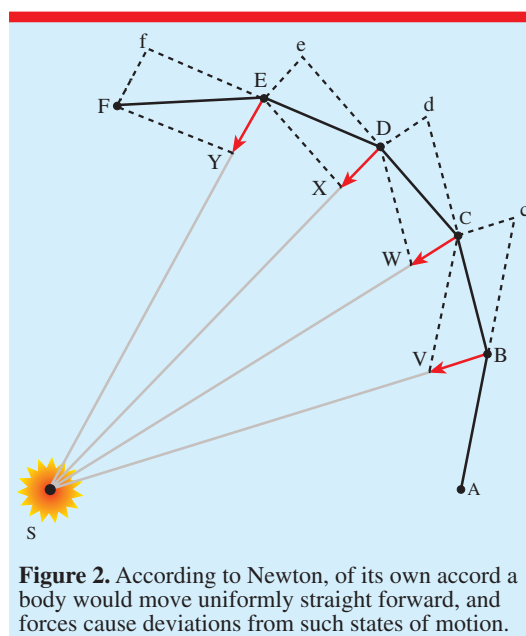
#### Core causal knowledge

Our ordinary concept of causation is one of ‘things going on as they are unless interfered with’ (Dummett 1978). Figure 1, an adaptation of a cartoon by Gotlib (1970), illustrates this idea. On the left we see a man taking a post-prandial stroll. On the right we see the same man having the happiest thought of his life. Clearly something must have happened in between to cause the change. The alleged cause is illustrated in the middle picture.

Of course, much more can be said about our ordinary concept of causality. For present purposes, however, it suffices to point out that causes effectuate *changes of state*. More formally, Descartes put it as follows: ‘each thing, provided that it is simple and undivided, always remains in the same state as far as is in its power, and never changes except by external causes’ (Descartes 1991, page 59).

#### Explanation of motion as a form of causal explanation

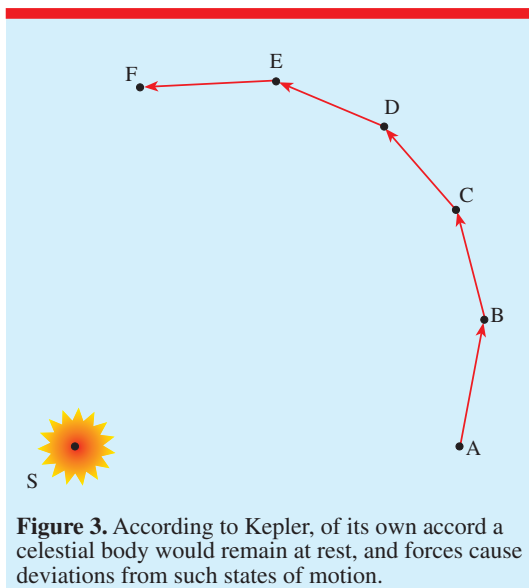
Explanation of motion can be seen as a special case of causal explanation. In this case one is concerned not with changes of state in general, but with changes of *state of motion*, and forces are the



**Figure 2.** According to Newton, of its own accord a body would move uniformly straight forward, and forces cause deviations from such states of motion.

effectuators of these changes. Let us consider the following examples.

*Newton.* In his first law, Newton explicitly states that of its own accord (force-free motion) a body would uniformly move forward in a straight line. Deviations from this motional state are caused by forces that act on the body. This is illustrated by Newton's construction method in figure 2 (see also Newton 1999, page 444). An attractive force directed towards the sun S influences the force-free continuation B–c of the motion A–B of a planet.

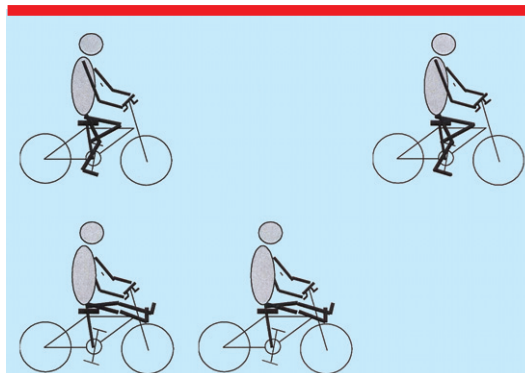


**Figure 3.** According to Kepler, of its own accord a celestial body would remain at rest, and forces cause deviations from such states of motion.

The actual motion B–C is the superposition of the force-free continuation and the deviation B–V caused by the force. Similarly for steps C–D, D–E, etc.

*Kepler.* Other assumptions for force-free motion are also possible. Kepler assumed *rest* to be the force-free motional state, at least for celestial bodies. In this case the construction is rather different (see figure 3). Here a force is required to ‘push’ the planet from A to B, from B to C, from C to D, etc, since of its own accord the planet would remain in one place. So Kepler had to somehow find forces that could ‘drag’ the planets along their paths (Kepler 1995, Stephenson 1994). Although Kepler’s theory of planetary motion does not have the same scientific status as Newton’s, at least it shows that one can have a serious go at accounting for planetary motion under the assumption of rest as the force-free motion.

*The man in the street.* A similar explanatory strategy can be seen in the explanation by the man in the street of why a cyclist should keep pedalling in order to maintain speed (figure 4). The simple answer is that if the cyclist stopped pedalling, he/she would come to a stop. In this scheme, the force takes the form of a personal influence (pedalling) and the force-free motion is the motion without this influence, i.e. to gradually come to a stop.



**Figure 4.** According to the man in the street, if the cyclist did nothing he/she would slowly come to a stop, but continuing to pedal prevents this from happening.

#### *A common explanatory scheme*

The specific explanations from Newton, Kepler, and the man in the street can now be seen to have the same basic structure.

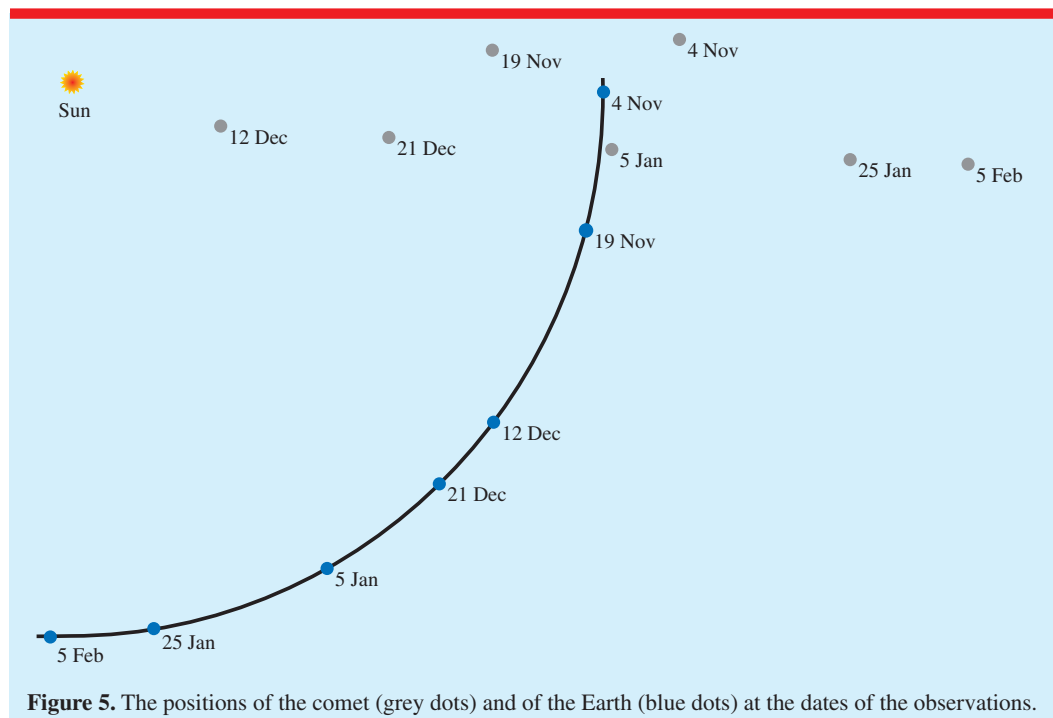
(A) Some assumption regarding the force-free state of motion, in combination with

(B) Some assumption regarding force laws to account for deviations from the latter state.

The components A and B of this structure are mutually dependent. As Friedman put it: ‘Theories of interaction and the notion of free—or inertial, or geodesic, or ‘naturally moving’—particle are intimately connected’ (Friedman 1983, page 121). The structure does not tell us *what* we ought to choose as forces, states, laws, etc. But it does set *constraints* on such choices; it offers an *explanatory scheme* into which the choices we make must fit. Hence it functions as a *regulative principle* to direct and guide an investigation into the motions of bodies (Nagel 1979, page 192).

#### **Eliciting the basic explanatory scheme as an advance organizer**

The main point of this paper is that the basic explanatory scheme, and the core causal knowledge in which it is grounded, can also serve to direct and guide *students’ learning* about how to explain the motions of bodies. We present in some detail how we have tried to achieve this with academically streamed students at upper secondary level (approximately 16 years of age).



**Figure 5.** The positions of the comet (grey dots) and of the Earth (blue dots) at the dates of the observations.

### *An intriguing problem*

We introduce the case of a comet that was visible in the sky on some evenings in the period November 1680–February 1681. The grey dots in figure 5 represent heliocentric renderings of the observed positions of the comet. The curved line represents part of the orbit of the Earth around the Sun<sup>1</sup>.

This case suits our educational aims for the following reasons.

- (1) It immediately raises all sorts of questions. Where was the comet located at the dates it was not observed? What was its orbit? And above all, what exactly did happen between late November and early December 1680, and why?
- (2) It provides for a rich variety of student explanations. These serve on the one hand for the teacher to elicit the basic explanatory scheme, and on the other hand this can subsequently form a useful guideline for further investigation.

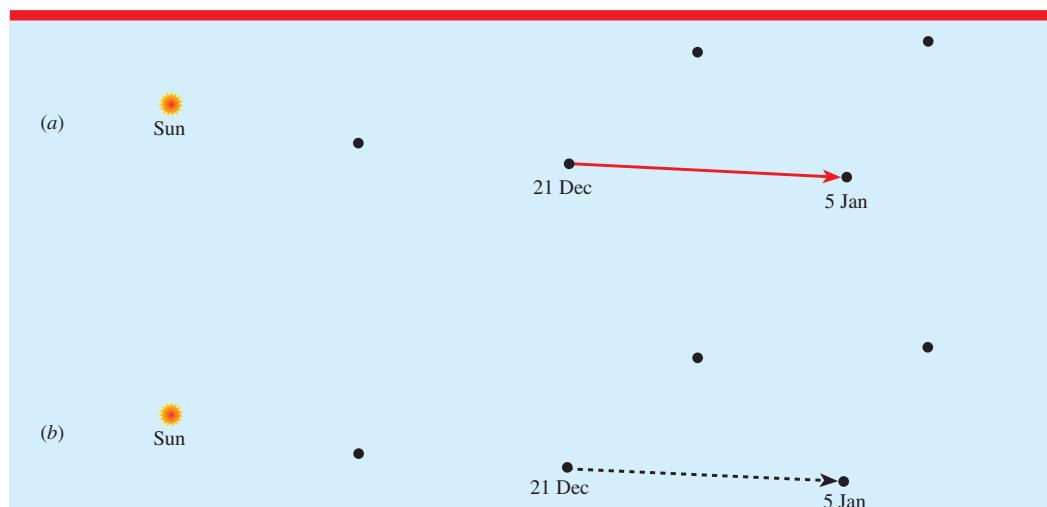
<sup>1</sup> Newton discusses this comet towards the end of Book 3 of the *Principia* (Newton 1999, page 916). In order to increase the geometric readability, we have drawn the comet and the earth in one plane. In reality, the planes in which the earth and the comet moved were nearly perpendicular.

Below we illustrate these points, based on experiences with students who discussed the case of the comet as part of our experimental course in mechanics.

### *A rich variety of student explanations*

In our try-outs the students indeed found the case of the comet intriguing. At first they were reluctant to commit their ideas to paper. Once they had been reassured, however, that the aim was not to 'guess' the correct trajectory of the comet but rather how they go about trying to explain its motion and the ideas underlying their approach, they contributed creatively and diversely. The following are examples of student explanations. In 'The basic explanatory scheme as a means for organizing the students' explanations' we will illustrate how a teacher can use these to elicit the explanatory scheme.

Regarding the trajectory of the comet, some students supposed that it travelled around the Sun, but at least as many suggested that it turned before reaching the Sun. Almost all the students thought that the comet did not 'turn' by itself, and identified the Sun as the cause of the change in direction. Concerning the influence of the Sun, some reckoned that it was attractive; others that



**Figure 6.** Alternative explanations of the comet's motion between 21 December and 5 January. (a) There must have been an influence because otherwise the comet would have come to a stop. (b) No influence is needed. The comet simply 'kept' the speed it already had.

it was repulsive; in some cases it was supposed to be attractive at first and later repulsive, thus making the comet turn. A range of mechanisms was suggested to explain these influences, such as magnetism and solar winds. Apart from the Sun, some students also thought that the Earth played a role: for example, that it drew the comet somewhat out of its orbit between 4 November and 19 November. Some students believed that the motion of the comet was no longer significantly influenced between 21 December and 5 January: the comet just carried on moving simply because it already was moving. Others thought that the Sun somehow must have pushed the comet away. At this point, all the suggested explanations are considered valid.

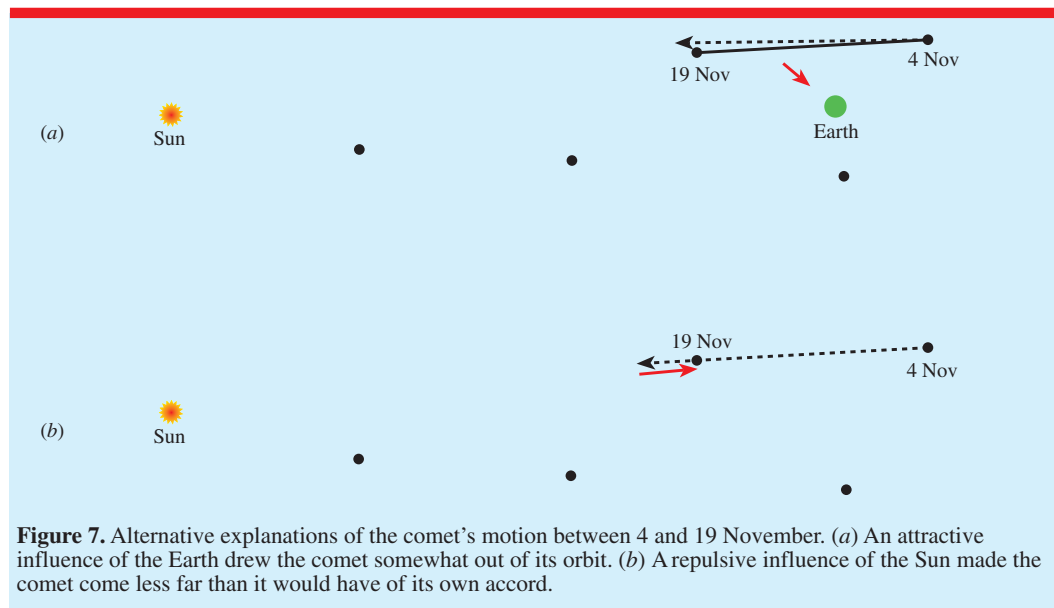
#### *The basic explanatory scheme as a means for organizing the students' explanations*

At first sight the task of the teacher to somehow order this great variety of ideas into a useful guideline would seem nearly impossible, but this is where the explanatory scheme comes in. The first step is to somehow make the explanatory scheme 'visible' to the students.

Component B, a characterization of force laws, is easily made explicit. However different in detail, all the students have ideas regarding sources and properties of the influences acting on the comet. But also component A, some

characterization of a force-free state of motion, can be shown to have played a role in the students' reasonings. For example, the idea that the turning of the comet had a cause rests on both components of the scheme, as follows. An idea about potential sources of influence (B) makes it plausible that for example the Sun *may* have been the cause. But it is the idea that the comet did not turn of its own accord (A) that implies that there *must* have been something to cause the change of direction.

The subtle interplay between the two components of the scheme can also be brought forward in connection with other sections of the comet's orbit. Consider for example whether or not the student thinks that some influence affected the comet's motion between 21 December and 5 January. Different answers to this question indicate different implicitly held assumptions about how the comet would have moved of its own accord, as illustrated in figure 6. Figure 7 shows alternative explanations of the comet's motion between 4 and 19 November. The common element is to explain the motion of the comet as a combination of (i) this is how it would have moved of its own accord (its force-free motion) and (ii) this is the deviation caused by some influence acting on it. The examples in figures 6 and 7 can be seen as intermediate stages on the way to formalized construction methods, as illustrated in figure 2 for Newton's assumption for force-free motion or figure 3 for Kepler's assumption.



**Figure 7.** Alternative explanations of the comet's motion between 4 and 19 November. (a) An attractive influence of the Earth drew the comet somewhat out of its orbit. (b) A repulsive influence of the Sun made the comet come less far than it would have of its own accord.

#### *The basic explanatory scheme as a directive guideline*

The aim for the students is to find out how to explain motion as precisely as possible. So even though at this point they can see how to fit their intuitive reasoning into an explanatory scheme, an important problem still remains: how to determine which of the many varied combinations of assumptions in fact serves the aim. In answering this question the basic explanatory scheme also serves as a directive guideline. It provides students with a structure to work with, and they know what types of element they need to fit into the structure. But they still need to find out how to fill in the details.

#### **Concluding remarks**

The case of the comet described above is part of an introductory course in mechanics designed as the basis for a PhD project in physics education.

#### *Overview of the course*

Very briefly, the course consists of the following.

- An introduction in which students get an impression of what mechanics is about, and its use or relevance.
- Making the basic explanatory scheme explicit, as described in 'Eliciting the basic explanatory scheme as an advance organizer'.

- Formalization of the explanatory scheme into a precise time-step by time-step construction method.
- Use of a computer to reduce the size of the time-steps, so that the precise trajectory of a body can be determined, given any combination of assumptions about the influence acting on the body and the force-free motion.
- Introduction of simplified versions of Kepler's and Newton's theories of planetary motion.
- Evaluation of the theories of Kepler and Newton.

In this last step, the students are guided by appropriate epistemological resources to decide between alternative theories. Does it make sense? Does it work? Does it work in every situation? In a computer-based modelling process of fitting and adjusting parameters, finally students arrive at a validated choice for Newton's theory.

#### *Some findings*

Our course has been tried out three times by two teachers during the period 2005–2008. On the whole, both students and teachers were well satisfied with our approach, but there were also some problems. Students, for example, are not keen to spend time learning a theory (Kepler's) that turns out to be 'wrong', although they do



generally appreciate that it is not always a matter of 'right' or 'wrong' but 'how' and 'why', and admit it probably helps to understand Newton's theory better. For the teachers the main difficulty is how to involve the students actively in the lessons, i.e. planning ahead, rather than just passively following the teacher's line of instruction.

With respect to understanding, the first impressions are that the students do come to appreciate mechanics as a powerful theoretical instrument with useful applications, this being significantly enhanced by having worked hands-on with the construction method introduced in the course. The students experience some difficulty in maintaining an overview of the various theories, the relation with their own intuitions, and the subtle grounds for choosing between theories. But on the whole the students come to a better understanding of Newton, especially his first law of motion, by also having studied Kepler.

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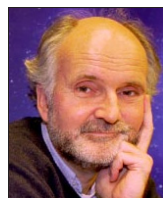
**Axel Westra** conducted a PhD study at Utrecht University on the possibility of tapping core causal knowledge in learning mechanics, which he completed in 2006. Since then he has been a high-school teacher of physics and general science at RSG Brokdele in Breukelen, the Netherlands.



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