EUR. J. SCI. EDUC., 1979, VOL. 1, NO. 2, 205–221

Spontaneous Reasoning in Elementary Dynamics

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It is commonly assumed that we think as we have been taught to think. The purpose of this paper is to show that even in physics where most people would imagine that they know nothing they have not been taught, we all share a common explanatory scheme of 'intuitive physics' which, although we were not taught it at school, represents a common and self-consistent stock of concepts and which, however wrong it may be, resists attempts to change or modify it. This 'intuitive physics' presents, at the very least, a considerable challenge to teaching. Also, it makes much of our teaching less effective than we usually assume it to be.

The work described here has its origins in practical teaching problems, and its ultimate aim is to contribute to an improvement of teaching. The immediate aim is, however, more modest: to attempt to understand how students actually think about some specific situations, and to describe and formulate that thinking. The topic chosen for this study is the relations between force, energy, and motion.‡ The ideas were studied only in their most elementary form, shorn as far as possible of mathematical and other difficulties. The questions asked of students were very simple, e.g. 'Is there a force?' or 'Will an object move or not?'.

Elementary ideas of dynamics form a particularly good starting point for the study of spontaneous reasoning: this is so because many of the ideas taught contradict very common kinds of spontaneous reasoning. For example, it is often thought intuitively that a ball thrown in the air keeps rising because it has been given an impulse to rise which is not yet used up; otherwise it would start to fall. In this kind of reasoning, a linear relation between force and velocity is assumed, rather than one between force and acceleration. (It appears that spontaneous reasoning can be formalized in terms of its own 'laws'!)

We shall show that such spontaneous reasoning is highly robust and that it outlives teaching which contradicts it. We shall also attempt to analyse in some detail how it works and what its consequences are. We shall see that it represents not just a few mistakes made by some students, but a way of thinking found in everyday conversation and in much that one reads; so much so that every one of us does, from time to time, reason in this way or, at least, has done so.

‡ Changes of reference systems have been studied by Saltiel (1978).

Spontaneous ideas in dynamics: outline of a model

(1) Force of interaction and 'supply of force'

The investigations described here use pencil-and-paper tests, each taking 20 to 30 minutes. The purpose is to focus on the students' predictions about a specific aspect of the motion of a body or bodies, and eliminating as far as possible other difficulties, especially mathematical ones.

For example, in figure 1 several simple systems are shown with their motion 'frozen' at one instant, with all the bodies having the same positions

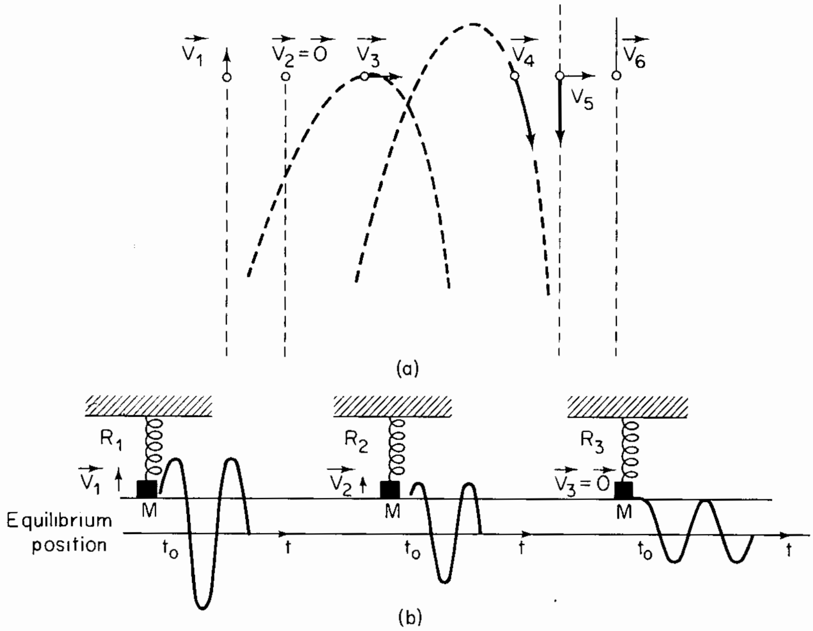

Figure 1. Two series of systems having identical positions but different motions

but different speeds and directions of motion, as indicated. In one version, the system is a set of juggler's balls captured in flight, all at the same height (figure 1(*a*)). In another apparently different, but in fact essentially similar version, the system is a set of three masses oscillating on the ends of vertical springs suspended from the ceiling, again all at the same height (figure 1(*b*)). The question is asked whether the forces acting on all the balls (or masses) are identical at the instant shown (air resistance is taken to be negligible). In both cases, the answer from elementary dynamics is that they are: the forces which are taken into account, i.e. the weights of the balls or masses, and the tension in the springs, depend solely on the positions of the bodies and not on their motion. The fact that the tension in the springs is proportional to their elongation (the same for all three) is even explicitly mentioned in the test.

From the formally correct point of view, the question is so obvious that one hardly dares ask it. What about the results? These are summarized in table 1 and show that the answer is not at all obvious when the student is given the motion as well as the position, and pays attention to it. (It is worth noting that the situations presented are designed so that the motions are not randomly chosen: most are chosen to be in the opposite direction to the resultant force.)

Table 1. Responses to questions about Figures 1(*a*) and 1(*b*)

NUMBER OF STUDENTS RESPONDING	QUESTION RELATING TO	STUDENTS' YEAR OF STUDY‡	THE FORCES ARE . . . *equal*	*not equal*	*(no reply)*
29	figure 1(*a*)	Last year of secondary school	39%	55%	6%
36		First year university	58%	42%	0%
226		First year university (Belgian)	44%	54%	2%
20	figure 1(*b*)	First year university	70%	30%	0%
95		Second year university	48%	40%	12%
49		Third year university	37%	55%	8%
14		Last year of secondary school (British)	64%	36%	0%
14		First year university (British)	57%	43%	0%
226		First year university (Belgian)	37%	49%	14%

‡ Students are French except where otherwise indicated.
Results for Belgian and British students were kindly supplied by Professor J. Deltour and Professor L. R. B. Elton, respectively.

These and similar experiments suggest that, for many students, there is an intuitive 'law' which can be expressed as a pseudo-linear relation between force and velocity, $\mathbf{F} = \alpha\mathbf{v}$, as follows:

(1) If $\mathbf{v} = 0$, then $\mathbf{F} = 0$, even if the acceleration $\mathbf{a}$ is not zero. (So, for example, in the questions mentioned above, we find in about 20 per cent of the answers statements like 'M_3 is in equilibrium', '$v_3 = 0$; therefore $F_3 = 0$', 'M_3 is at rest, so $F_3 = 0$', despite the fact that for the spring system the equilibrium position is explicitly shown as being below the positions of the masses (figure 1(*b*)).

(2) If $\mathbf{v} \neq 0$, then $\mathbf{F} \neq 0$, even if $\mathbf{a} = 0$. Thus, a mass with non-zero velocity passing through its equilibrium position (while oscillating on a spring) is seen as being subjected to a non-zero force, even by some third-year university students (the force is, of course, zero). Similarly, a ball thrown horizontally is seen as being subjected to a horizontal force long after having been released!

(3) If the velocities are different, the forces are also different, even if the accelerations are the same. This 'law' was supported by comments of the type: 'The motions are not the same, so the forces are different'; 'The velocities are different, so the forces are different too'.

The model accounts adequately for many of the findings, but needs some refinement to take account of others. We find, for example, that students correctly associate force with acceleration (as they have been taught) and not with velocity (as we have seen them do above) if they are presented with an equation of motion and have to calculate the force, or when they are presented with a question such as, 'If the same force acts on two identical masses, are the motions necessarily identical?' In the latter case, over 80 per cent of first-year university students correctly replied that they are not, since this depends on the initial velocities.

To take this into account, we must suppose that students use different notions of force depending to the question asked, even if these notions serve the same purpose, namely to explain the motion. These different notions can be described as follows (see also tables 2 and 3):

(*a*) *Force of interaction,* denoted here by F_{act}, is a function of the *position* of a moving body, and determines the rate of change of velocity; i.e., $\mathbf{F}_{act} = m\mathbf{a}$. When this notion occurs in students' reasoning, it indicates a 'static' or 'local' way of looking at a situation by considering first the positions of the objects. This notion is talked about as 'the force acting on . . . [the mass]'. It is taken to be sufficient to explain motion when the force acts in the same direction as the one in which the motion occurs. This notion of force is also applied when no intuitive data are presented in a problem concerning motion.

(*b*) Another notion of force will be called (following a student's comment) *supply of force* and denoted by F_s. This notion may be thought of as 'the force in a body which keeps it moving'. It is used in situations such as those described (figures 1(*a*) and 1(*b*)). It follows the relationship $F_s = \alpha v$ (more nearly a scalar than a vector relation). Strongly connected with motion, the 'supply of force' is used when the motion is given, or is easy to see or imagine, and when the motion seems incompatible with the (true) resultant force (because the motion is opposed to the force, or because the motion is zero in spite of a non-zero force, or because it is non-zero in spite of a zero force).

The function of 'supply of force' is to account for the existence of motion. The idea allows the initial cause of a motion (e.g. the movement of the thrower's arm) to be linked with its visible effect (the motion), provided that the cause can be passed 'into' the moving body. Students thus refer to 'the force *of* the mass', although it is not clear whether they actually think of a force or of something close to energy.‡ Indeed, some comments explicitly make the link: 'The force must be equal to the kinetic energy . . .'. This notion, part vector and part scalar, is reminiscent of the notion of 'impulse' in ordinary language and of 'impetus' in pre-Galilean dynamics.

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‡ It is impossible here to say more about this. Let us merely mention that although the concept of energy is sometimes used correctly (especially in connection with potential energy in situations like in figure 2(*b*)), in other situations it is inextricably mixed with the concept of force in a single undifferentiated explanatory complex. In this case it means the same as what we have called 'supply of force'. Much remains to be done to analyse precisely the nature of spontaneous reasoning concerning energy in its different aspects (kinetic, potential, etc.).

Table 2. Different notions of 'force' and the characteristics associated with them by students

	SYMBOL	TYPICAL FORMULATION	PHYSICAL NATURE	LOCALIZATION	MODEL USED
Force of interaction	F_{act}	'Force acting on the mass'	Orientated (vectorial?)	Function of position	$\mathbf{F}_{act} = m\mathbf{a}$ $\mathbf{a}$ = acceleration
'*Supply of force*'	F_s	'The force *of* the mass'	Mixed scalar-vector. Force-energy confusions	A property of the whole motion: spatio-temporal delocalization	$F_s = av$
Inertial force	F_i	'Inertial force'; 'Inertial reaction'	Orientated (vectorial?)	Occurs at an instant: temporal localization	$\mathbf{F} = -m\mathbf{a}_e$ $\mathbf{a}_e$ = externally imposed acceleration

Tables 2 and 3 summarize the nature and properties of these two 'forces', and the condition under which they are used in students' reasoning. They constitute the core of an interpretive model which makes it possible to predict the probable type of answer which will be given to different types of question. The two notions as defined above are clearly extreme cases, and a particular student may well oscillate between them. Even so, the model describes general tendencies reasonably well.

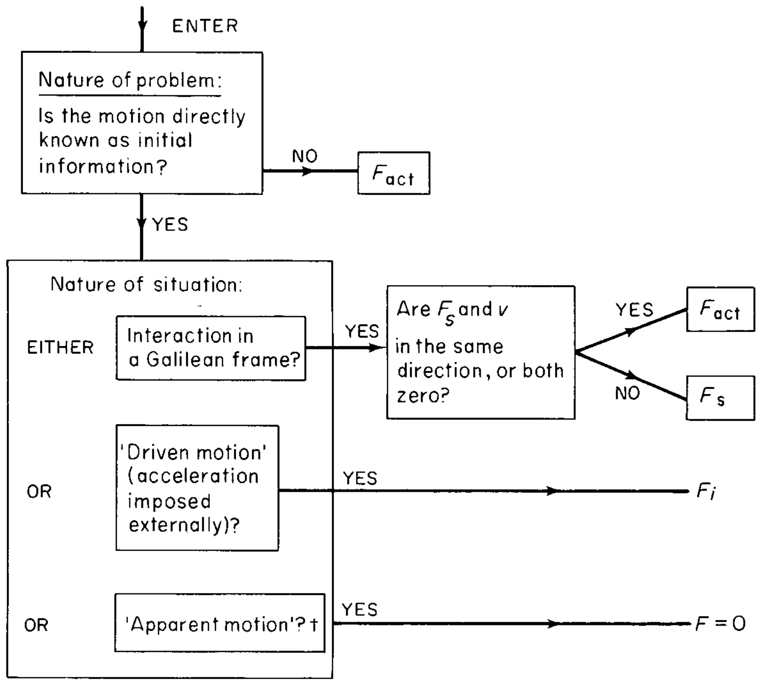
(2) *Centrifugal force*

Tables 2 and 3 mention one other kind of 'force', namely *inertial forces*, denoted by F_i. These are the 'forces' which cause the subway (tube) traveller to sit down unexpectedly when the train starts, or which throw the passenger in a car against the door when it corners sharply. They are invented to account for observed phenomena inside accelerated frames of reference, although they do not exist within the Galilean formalism. 'Centrifugal force' is one example of such forces: it is a convenient notion for interpreting observed motions inside a rotating frame of reference (such as a car taking a bend). It should be pointed out that this notion is frequently prevalent in people's everyday thinking, even when everything to be accounted for occurs in a Galilean frame and there is no need for this artefact.

Consider the situation depicted in figure 2. Here, the notion of inertial force seems to be introduced to allow the intuitive assumption $\mathbf{v} = 0 \Rightarrow \mathbf{F} = 0$ to apply along the normal to the trajectory: 'Along the radius, the tension in the thread balances the centrifugal force of the stone'.

This conception may seem harmless (and may be so), but it is worth

Table 3. Basic flow diagram of a model of spontaneous reasoning in dynamics: conditions under which notions of force in table 2 are used



† This type of situation is not elaborated in the paper. It can be illustrated with a simple example: a traveller in a train never imagines a force to be acting on a tree which he sees passing the window.

noting that it excludes completely any mention of the reference frame, as confirmed by another experiment (see question G given in the appendix). Moreover, this intuitive point of view subordinates the use of 'centrifugal force' to other conditions, in that it is used only if the motion can be thought of as stationary or at least as a global entity, and if no other force seems to fulfil the balancing role.‡

(3) 'Local' or 'global' reasoning

Crude though the present model may be (it has been further simplified for this paper), it has some important implications. These are that:

(*a*) Spontaneous reasoning uses notions that may have the same name ('force' or 'energy') but which are different and have different properties.

‡ Consider question (P) in the appendix, which concerns a pendulum. Centrifugal force is only used in spontaneous reasoning if the weight of the oscillating mass has no centrifugal component (case 4).

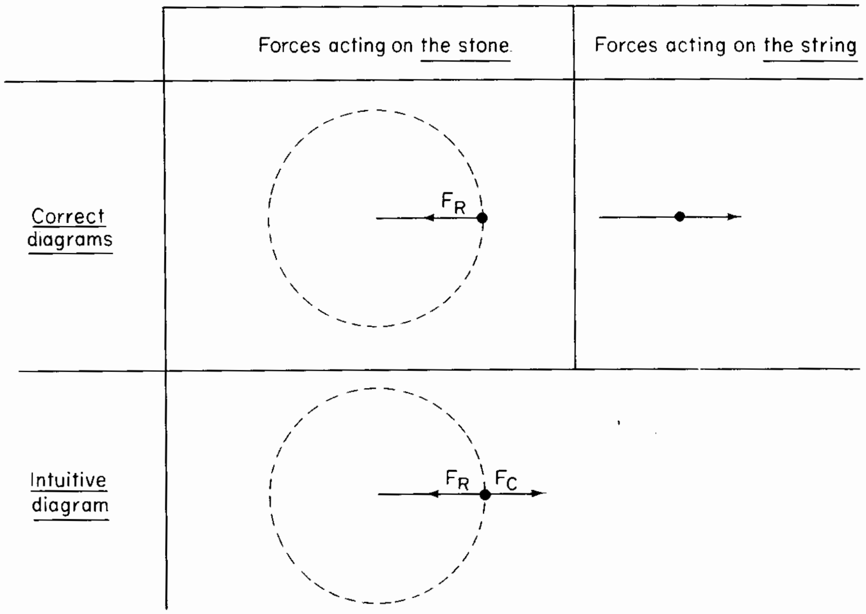


Figure 2. Force diagrams for a stone turning at the end of a string

(*b*) Each of these notions is used in different circumstances which can be broadly classified. The conditions for their use differ somewhat from the formalism which students have been taught.

In this structure of spontaneous thought, two different types of approach to thinking about motion can be discerned:

(*c*) A 'local' or 'static' type, which considers the *positions* of the objects in the system, or its *state*, and which makes a *local* analysis of the motion, and thus uses force of interaction only.

(*d*) A 'global' one, which starts from the *motion* or from the *evolution* of the system. It regards a motion in a much more *global* way, and makes use of 'supply of force' motion.

Action and reaction

The physical system shown in figure 3 permits the illustration of both the consequences of reasoning with 'supply of force' and its connections with the concepts of action and reaction. The system is simply a mass at rest on top of a spring. The question is: 'How far has the mass to be pushed down so as to rise off the spring when it is released?'

Most students answer to the effect that the force of the spring must overcome the weight of the mass. (This condition is in fact either insufficient or impracticable, according to whether it is applied to the height of the mass when it is released, or to the height at take-off. The last point is not specified in most cases.) Such reasoning clearly reveals confusion between force and energy.

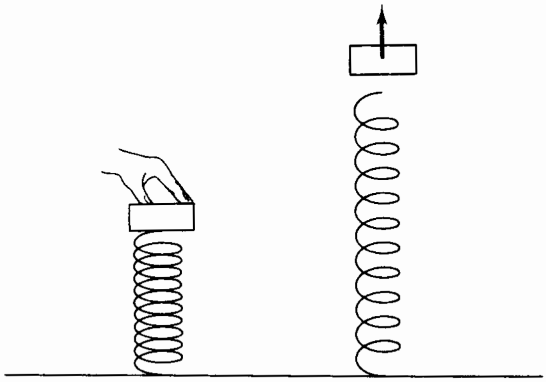


Figure 3. A mass rising off a spring

Implied in these replies is the concept of 'supply of force' which leads to wrong conclusions being drawn. But one can go further in analysing how the ideas are used. The 'force' in the direction of motion results, in intuitive reasoning, from an unbalanced conflict between two forces. As one student said: 'The equilibrium must be broken'. These two forces, one ascribed to the mass and the other to the spring, are often also described as 'action' and 'reaction'. Students are then led to write inequalities between action and reaction, following the implicit sequence:

(1) At equilibrium (no motion) action equals reaction.
(2) When there is motion, the action exceeds the reaction or *vice versa*, the resultant being in the direction of motion.

In the Newtonian scheme, of course, action and reaction are always equal, whatever the motion. The intuitive explanatory scheme has its own different laws, different requirements, and different kinds of motivation. One simple motivation is that by ascribing forces to objects it becomes possible to avoid specifying what acts on what. For example, in order to lead to the statement, that the action of the spring overcomes the reaction of the mass, spontaneous reasoning has to associate the weight with the *object itself*, rather than to see it as an interaction which would then have to be specified further. When the weight, as the force *on* the mass due to the Earth, has been converted into the weight, as the force *of* the mass, this force may act on the mass or on the spring, as one chooses. So one frequently reads, 'the mass applies its weight to the spring'.

A similar shift of the thing on which a force acts appears in the intuitive scheme which is used to explain 'centrifugal force' (see Section 1.2 and figure 2). The circular motion of a stone on the end of a string, for example, is spontaneously seen as an equilibrium situation (radially), so that there is an intuitive need for two 'equal' and opposite forces. Two such forces are forthcoming, namely:

(*a*) The tension in the string, acting *on* the stone, towards the centre.
(*b*) The centrifugal reaction *of* the stone (which is simply the Newtonian

reaction exerted *by* the stone *on* the string transformed, to meet the needs of the intuitive argument, into a force '*of*' the stone and then into a centrifugal force acting now *on* the stone).

That is to say, in summary, that the ideas of action and reaction provide an opportunity to look at the specific effects of two general tendencies in spontaneous reasoning. These are:

(i) The tendency to attribute physical quantities (e.g., a force or energy) to objects themselves.
(ii) The tendency to look for a force (or feel a need for a force) in the direction of motion in order to account for the motion.

The consequences of these tendencies are, in this instance:

(1) Shifts in the objects on which forces act.
(2) Unequal action and reaction, with one overcoming the other in the direction of the motion, the two being equal only when there is no motion or when there is 'radial equilibrium'.

Conclusion

The examples given show a number of very general tendencies in spontaneous, intuitive mechanical reasoning. A wider study (Viennot 1977) traced the same reasoning in a wide variety of sources, including newspaper articles, popular science journals, and even in science textbooks. Teachers tend to make similar mistakes when they answer in a hurry.

The intuitive scheme is, thus, widespread and tenacious. It resists the teaching of concepts which conflict with it, and it reappears even in the expert when he or she lacks time to reflect. Such tenacity is probably connected with the self-consistency of the scheme.

Interestingly, the intuitive scheme is very close to a rather evolved scheme of historical thought. It is much closer to the impetus theory than to Aristotle; also, it is not primitive in that it goes far beyond the thought of young children. It represents a worked-out and effective system of thought, despite being in conflict with the yet more worked-out and effective Newtonian scheme. It deals without contradiction with most situations encountered in daily life.

If the spontaneous scheme is to be replaced or overcome, a major teaching effort is needed which goes beyond the conventional teaching of the Newtonian scheme alone. As we have seen, the latter results merely in juxtaposing academic knowledge and the intuitive system, laying one on the other without conflict between the two. Teaching of the Newtonian scheme will only be fully effective when students are led to look at the discrepancies between it and their spontaneous ideas.

It follows that students should be helped to make explicit their own intuitive reasoning with all its consequences, and to compare this with what they are taught. This is essential if students are to play an active role in the process of abstraction, and if they are to understand the nature of a formal model. Indeed, during the investigations reported here, a very real measure of satisfaction was found amongst students who, through tackling the questions, arrived at a clearer view of their own thoughts.

To do any of this, teachers need two things:

(1) A clear understanding of spontaneous reasoning, and of the type of reasoning likely to be evoked by different types of problem or situation.
(2) Simple tools to make students aware of their intuitive tendencies.

Further research is needed in these two aspects, in relation to this and to other fields of science, with the objective of deepening our basic knowledge of how people think and of making such knowledge accessible to science educators and teachers.

Acknowledgement

The help received from Mr J. Ogborn in the preparation of the English version of this paper is gratefully acknowledged.

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Appendix

A. Some pedagogical implications‡

I. Some types of wrong reasoning seem to suggest obvious remedies:

(1) '$V_3 = 0 \Rightarrow F_3 = 0$, the mass is at equilibrium, therefore the force is zero'. This answer comes from confusing the statement '$V_3(t) = 0$' with '$V_3(t) = 0$ *for any t*'. Here the equilibrium position is associated with a zero motion rather than with a zero force. Obviously, an exclusively static introduction of equilibrium can only reinforce this already quite natural tendency and is best avoided (figure A1).
(2) Decelerated motion gives rise to more difficulties than accelerated motion because interaction forces seem incompatible with the motion. It may be that decelerated motion is not given often enough as an illustration of the law $\mathbf{F} = d(m\mathbf{v})/dt$ (figure A2).

‡ The research described in this paper did not include any systematic testing of new pedagogical procedures. Suggestions made here derive directly from above experiments and convey the writer's views or personal teaching experience.

(3) Various kinds of motion (uniform rectilinear, circular, or uniformly accelerated motion) are often considered as wholly different phenomenon, so that students say 'the motions are different, therefore the forces are different too'. Undoubtedly, this tendency is not countered enough in teaching, at least not in France, by exercises focussing on local characteristics of a system. We must bring out the idea that such characteristics are compatible with an infinity of different motions having the same acceleration (figure A3). Step-by-step calculations of trajectories are excellent exercises in that respect.

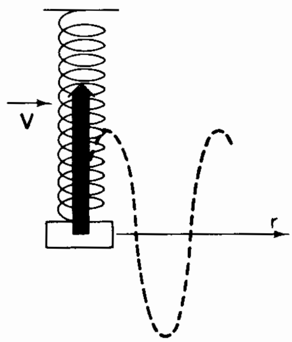


Figure A1. Equilibrium position, even if the body is in motion

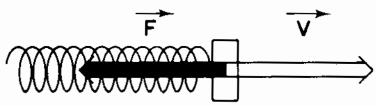


Figure A2. F $=\frac{d(m\mathbf{v})}{dt}$

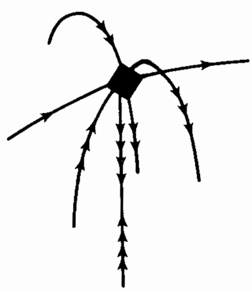


Figure A3. A position of a mass with different motions (but the same acceleration)

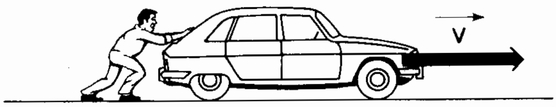


Figure A4. A breakdown: the action of the driver on the car is not larger than the reaction of the car on the driver

(4) Very often, Newton's third law is only illustrated by static situations, or interactions from a distance. The most confusing case should also be considered: two bodies in contact, each pushing or pulling the other (figure A4). It must then be emphasized that:
  (*a*) The action of the first body on the other, though in the same direction as the motion, is not larger than the reaction of the second on the first.
  (*b*) It is useless to predict the direction of the motion to compare forces which are *not applied to the same body*.
  (*c*) Comparisons between energies ($E_1 > E_2$), often looked upon as equivalent to comparisons between forces ($F_1 > F_2$) are still more irrelevant to this question.

(5) Changes of frames of reference give rise to particularly strong conflicts between intuition and taught formalism. They merit an important place in the teaching of mechanics, not only because they are difficult (which could deter) but also because they ruthlessly reveal mistakes which are latent in problems with only one frame of reference.‡

II. These few remarks immediately reveal the limitations of such remedies: 'to say', 'to show', 'to illustrate', 'to emphasize'. Experience of teaching shows only too well how ineffective such prescriptions can be. But they should be somewhat more useful, as they will enable students to take active part in comparing the taught formalism with something in which they are concerned more strongly: spontaneous reasoning.

In that respect, questions such as those described above seem to provide very stimulating opportunities. Others (see below, for example) can be used to analyse in detail misconceptions associated with problems. The author's personal and limited experience is that such exercises have positive and lasting effects.

B. Sample questions

Question G

Text:
You are in a plane flying *always horizontally*. You put the ice-cube of your

‡ See, for instance, question G in this appendix; attention should also be drawn to investigations by Saltiel (1978).

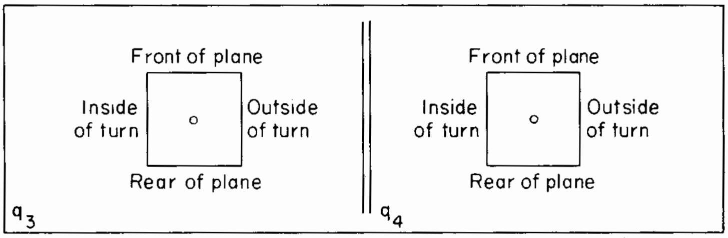
whisky on a perfectly smooth (frictionless) and horizontal table. At time t_0 you release this ice-cube without any impulse. Will it move in any direction in either of the following cases? If Yes, which one? Explain.

The plane is . . .

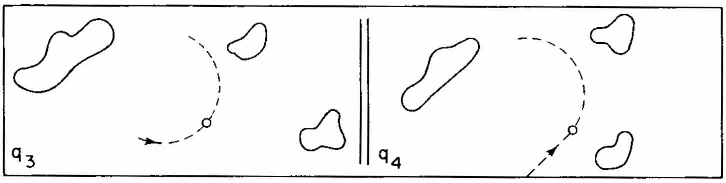
1. Flying in a straight line at constant speed ......
2. Flying in a straight line and accelerating ....
3. Making a turn at constant speed ....
4. Beginning to turn at time t_0, at constant speed

YES	NO

For the two last cases (q_3 and q_4), draw the trajectory of the ice cube:
(a) on the table, in the plane



(b) in the sky, as if plane and table were invisible, and only the ice cube visible.

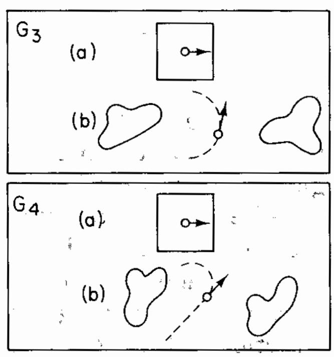


Two points were orally emphasized:

- the text is not realistic: a plane making a turn slants
- one asks only a start direction, and not a complete trajectory.

Correct answers:

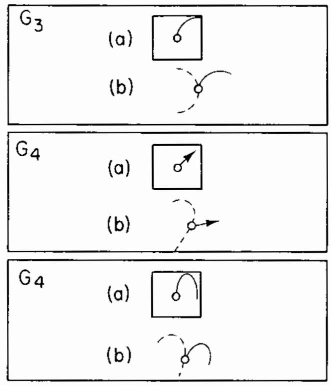
q_1: NO
q_2: YES, toward rear
q_{3a} and q_{4a}: YES, in a centrifugal direction
q_{3b} and q_{4b}: YES, tangential to the trajectory.



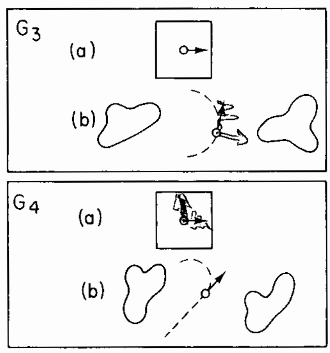
Questions 3 and 4 are identical, for the only things mattering are the initial velocity of the ice cube and the forces acting on it for time $t \geqslant t_0$.

Frequent mistakes :

- Answers transposed directly from one frame of reference to the other one:



- Questions 3 and 4 answered in a different way
- when combined, these two mistakes result for example in this answer:

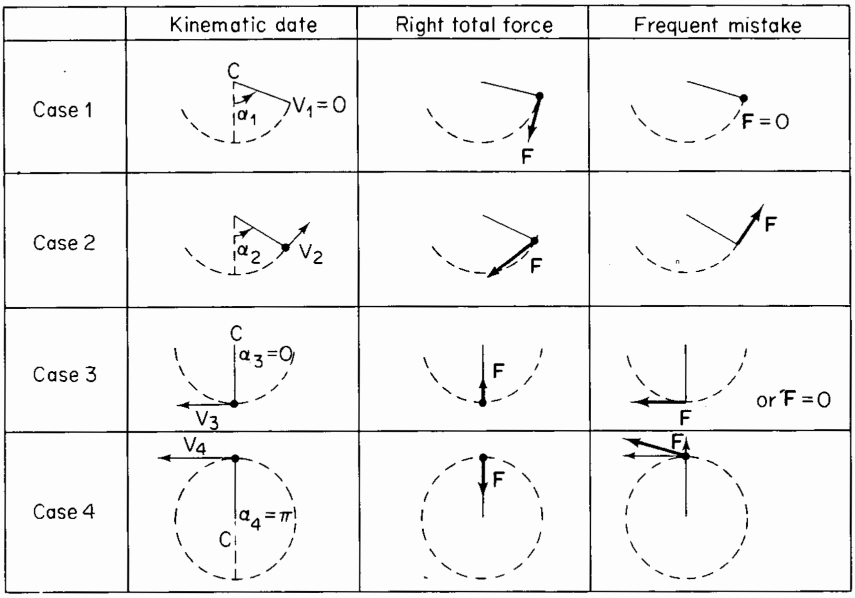


Question P

Text :

A point mass m freely oscillates (diagram 1', 2, 3) or turns diagram 4) in a vertical plane, at the end of a tight string whose length is l, whose mass is negligible, and whose other end is fixed at point C. Frictions are neglected. In each case below, trajectory (dotted line), velocity V, and angular position a of mass m are sketched.

On each diagram, draw the total force $\mathbf{F}$ acting on mass m as well as its normal $\mathbf{F}_N$ and tangential $\mathbf{F}_T$ components. Estimate these components as functions of m, g, l, a_1, a_2, $\mathbf{V}_2$, a_3, $\mathbf{V}_3$, a_4, $\mathbf{V}_4$ and explain your answers.



Summaries

English

The scope of this study was to explore and analyse spontaneous reasoning of students in elementary dynamics, from the last year at secondary school to the third year at University.

A set of investigations involving several hundred students (mainly French, but also British and Belgian) showed surprising rates of wrong, or right, answers, which are very stable from one sample of students to another. It seems difficult to attribute these results solely to school learning. But they can be reasonably well accounted for if we assume a spontaneous explanatory system, relatively unaffected by school learning.

In particular, students seem to use in their reasoning two different notions of dynamics, usually designated by the same word: 'force'. To detect which of these two notions has, in fact, been used, one must look at their properties: one of these 'forces' is associated with the velocity of a motion whilst the other one is associated with its acceleration. Likewise, the part played by energy in these two notions is distinctly different.

It is possible to set up, and roughly classify, the types of questions which give rise to each notion in spontaneous reasoning. This model, where inertial forces are also included, makes it possible, with a minimum of hypothesis, to account for answers on a wide range of topics, such as: free fall, oscillating systems, 'accelerated' frames of references, third law of dynamics.

More generally: when confronted with a physical system, students may first consider the system as *it is*, with its geometrical and physical characteristics *at time t*, or consider mainly the *evolution of the system*, and look for a causal explanation. While compatible in Newtonian formalism, these viewpoints lead students more often to right answers in the first case than in the second one, the explanation being then often confused with quasi-animistic arguments, and loosely located in time.

Some teaching consequences can be drawn from these investigations. Some of them, of a relatively technical nature, follow more or less directly from the wrong answers reported here. But the most important one concerns the very principle of these investigations: they provide an opportunity for the students involved to make an extremely useful self-analysis and to learn to distinguish between learned formalism and spontaneous reasoning and, consequently, to master both of them somewhat better.

Deutsch

Die dargestellte Untersuchung hat zum Ziel, das spontane Denken von Studenten in elementarer Dynamik zu erfassen. Die untersuchte Population umfasst Studenten vom Ende der obligatorischen Schulzeit bis zum Diplom an der Universität. Die Untersuchung umfasst mehrere Erhebungen bei 2.000 Studenten (hauptsächlich in Frankreich, aber auch im Vereinigten Königreich und Belgien). Der interkulturelle Vergleich zeigt eine erstaunliche Übereinstimmung in den Denkabläufen. Das gilt in gleicher Weise für die physikalischen Fehler wie für die spontan richtigen Antworten.

Die spontanen Denkprozesse der Studenten in elementarer Dynamik können nicht ausschliesslich mit dem Physikunterricht in der Schulzeit erklärt werden. Es gibt offensichtlich ein spontanes Erklärungssystem für Fragen der elementaren Dynamik, das nicht stark durch den Unterricht beeinflusst wird.

Die Studenten scheinen insbesondere in ihrem Denken zwei unterschiedlich bezeichnete Begriffe zu verwenden, aber mit dem Ausdruck 'Kraft' (force) zu belegen. Ein Begriff, der mit dem Ausdruck 'Kraft' bezeichnet wird, bezieht sich auf die Geschwindigkeit der Bewegung, der andere auf die Beschleunigung. Die Bedeutung, die der Begriff 'Energie' bei diesen zwei Begriffen einnimmt, ist sehr unterschiedlich.

Die Studenten der Population verwenden die beiden Begriffe nicht zufällig. Man kann die physikalischen Fragestellungen, in denen sie die unterschiedlichen Begriffe verwenden, grob klassifizieren.

Diese Klassifikation, die auch die Trägheitskräfte umfasst, erlaubt, mit wenigen Hypothesen die Antworten auf verschiedene Fragestellungen zu interpretieren, so auf den freien Fall, oszillierende Systeme, nicht galileische Bezugssysteme, actio und reactio.

Oder allgemeiner: Der Student kann, wenn er ein physikalisches System vor sich hat, dieses entweder so, wie es sich präsentiert, mit seinen kennzeichnenden geometrischen und physikalischen Eigenschaften charakterisieren oder sich für die Entwicklung des Systems interessieren und eine Erklärung suchen. Im ersten Fall sind die Versuchspersonen häufiger erfolgreich als im zweiten. Im zweiten Fall, in dem die Erklärung häufig durch quasi-animistische Argumente gekennzeichnet ist, geben sie die Antworten häufig zur unrechten Zeit.

Aus den Untersuchungen kann eine ganze Reihe didaktischer Konsequenzen gezogen werden. Einige, relativ technische, sind durch die hier beschriebenen Fehler bezeichnet. Daneben gibt es fundamentale Konsequenzen. Im Verlauf der Untersuchung hat sich gezeigt, dass die Art der Fragestellung und des Vorgehens in Wirklichkeit neue physikalische Lernprozesse ermöglicht hat. Die Versuchspersonen haben verschiedene physikalische Denksysteme in sich selbst kennengelernt und miteinander verglichen.

Die Versuchspersonen haben den Formalismus, den sie gelernt haben, mit dem spontanen Denken vergleichen und die verschiedenen physikalischen Denksysteme beurteilen können.

Français

L'étude résumée ici a pour but d'explorer et d'analyser les raisonnements spontanés d'étudiants en dynamique élémentaire, depuis la fin de l'enseignement secondaire jusqu'au second cycle universitaire. Une série d'enquêtes portant sur 2000 étudiants environ (Français, essentiellement, mais aussi Britanniques et Belges) fait apparaître des taux surprenants d'erreurs, ou de réponses exactes, étonnamment stables d'une population à l'autre.

Il semble difficile d'attribuer uniquement ces résultats à l'enseignement scolaire reçu jusque là. Ces réponses, en revanche, s'organisent assez bien si l'on admet l'existence d'un système explicatif spontané relativement peu affecté par l'enseignement.

En particulier, les étudiants semblent utiliser dans leurs raisonnements deux notions dynamiques différentes désignées, le plus souvent, par le même terme: 'force'. C'est par les *propriétés* qu'ils donnent à ces notions que l'on peut détecter celle qu'ils utilisent dans tel ou tel cas. Ainsi l'une de ces 'forces' est associée à la vitesse du mouvement, alors que l'autre est associée à l'accélération. De même la part que prend l'*énergie* dans ces deux notions est nettement différente.

Les types de questions qui mettent en jeu l'une ou l'autre de ces notions ne sont pas indifférents et peuvent être, grossièrement, classés.

Cet embryon de modèle, qui englobe également ce qui concerne les forces d'inertie, permet d'interpréter avec relativement peu d'hypothèses, des réponses portant sur des points aussi variés que ceux-ci: corps en chute libre, systèmes oscillants, référentiels non-galiléens, loi de l'Action et de la Réaction.

Plus généralement; en présence d'un système physique l'étudiant peut regarder d'abord le système tel qu'il est, avec *ses caractéristiques géométriques et physiques à un instant précis*, ou bien s'intéresser surtout à *l'évolution du système* et en chercher une explication causale. Conciliables dans le formalisme newtonien, ces points de vue conduisent en fait plus souvent les étudiants au succès dans le premier cas que dans le second, où l'explication est souvent marquée par des arguments quasi animistes, et mal située dans le temps.

Quelques conséquences pédagogiques peuvent être tirées de ces enquêtes. Certaines, relativement techniques, sont dictées plus ou moins directement par les erreurs décrites ici.

Mais la plus importante concerne le principe même de ces enquêtes: celles-ci ont été l'occasion, pour les étudiants interrogés, d'une auto-analyse extrêmement fructueuse.

Les étudiants en effet ont pu mesurer là, sur quelques points bien délimités, la distance qui sépare le formalisme appris du raisonnement spontané, et se rendre par là un peu mieux maîtres de l'un et de l'autre.