An experience teaching Newton's Laws

Salvador Jara-Guerrero
Departamento de Física, Universidad Michoacana de San Nicolás de Hidalgo
Apartado postal 139–C, 58260 Morelia, Michoacán, México

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Abstract. Results from an experience teaching dynamics at college level are presented. The classroom strategy gives special attention to the treatment of the most common misconceptions. The main aim of the paper is to report this attempt to put some theoretical ideas into practice.

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Alternate Conceptions and Common Sense Theories have become one of the most popular subjects of research in physics education within the last ten years. What research shows is that common sense misconceptions are so stable that conventional instruction has little effect on them [1,2]. So, considering the small number of opportunities for learning physics available during the educational life, it is important to improve the efficiency of instruction if we are to have scientifically literate citizens and want to encourage the formal study of scientific disciplines. The consequences of not correcting erroneous common sense beliefs early during instruction are not only the students' failure in understanding the content of that particular course; but also, that they represent strong limitations to future instruction and might become a real handicap in understanding the basics of everyday phenomena, as well as popular scientific literature for those who have to leave school early. The latter can be of minor importance if people are going to take several courses, though in Mexico less than 15% of the students who start elementary school go to college.

One of the most studied topics has been the concept of force. Results show that students, no matter their level of education and even after having passed the general physics course at university level, hold misconceptions about it [3,4,5,6,7].

— Students think of force as something that always acts in the direction of motion.

— Force is considered by students as a necessary condition for motion: if there is no force acting on an object, it has to come to rest.

— Newton's Second Law is usually misinterpreted; it is applied to individual forces rather than to the resultant or net force acting on a body.

— Internal forces are frequently considered responsible for changes in overall motion.

— Students have the idea that heavier bodies should fall faster.

— The absence of air is associated with the absence of gravity.

— Students commonly use centrifugal forces to explain curved movement, without taking into account the reference system.

— Independence of vertical and horizontal components in projectile motion is not recognized.

Students' ideas are not only isolated concepts different from those defined by science, but also structures with internal coherence (alternate theories) which are used to explain everyday phenomena. The model students employ to explain motion, for example, is an answer to the question "why does it move?", instead of to the question "why does it change its state of motion?". Within this model exists the underlying idea that motion is a "forced" state and that only rest is a situation of equilibrium; however, the students' paradigm is sufficient to explain everyday phenomena in certain practical situations.

I can think of at least three reasons to account for the existence of "aristotelian" models. The first is a fragmentary utilization of Newton's Laws, that is, there is a tendency to employ each Law independently from the others. Additionally, in everyday phenomena, motion is far from appearing as a natural situation. And third, the way dynamics is usually taught.

The Newtonian vision is not a set of independent pieces to be used at will, but a system where the components (Laws) are related to each other and have real meaning only when considered together.

When students think of force they don't usually take into account that forces come from interactions; if they forget this point, it is easier for them to become confused about the direction of the force. Besides, the fact that forces are external is not taken into account. Frequently textbooks use acceleration to define the direction of force, but the former concept seems to be as difficult to understand as that of force [8]. An obstacle almost all students have to overcome is the model they hold even before having taken the first mechanics course, which usually differs greatly from the model accepted by science. However, as we said before, the students' models are used successfully to explain everyday motion, at least in specific situations. I think a better understanding of forces as the effect of interactions may help students to overcome the misconceptions mentioned above.

As an exercise in dealing with students' misconceptions, I taught a general physics course to 24 freshman biology students at the University of Michoacán [9], greatly emphasizing interactions, and using an analogy between what students call force and momentum [10,11].

On the other hand, the proposal is based on the importance Piaget gives to conservation quantities. According to him, in fields not yet structured by conservation notions, new logical elementary relations such as transitivity and commutability are not observed either [12]. Within the Ausubelian approach, the conservation of momentum can be used as an advanced organizer which is one of the most general and inclusive ideas of the discipline, to serve as conceptual "anchorage" for subsequent learning [13].

Previous to the course, interviews were held with all the students in order to explore their conceptions of motion (Figs. 1 to 4).

Misconceptions found can be summarized as follows:

— Forty-two percent thought that bodies couldn't fall on the moon; half of these thought the absence of atmosphere was the reason [14].

— Eighty percent explained that objects moving on earth reach rest because they "lose" force; 20% didn't give any further explanation and 60% thought air, friction or gravity were responsible for this loss.

— Twenty percent said celestial bodies don't come to rest because their trajectory is in equilibrium.

— Eighty-eight percent identified the direction of force as being the same as that of velocity [15].

One point I would like to emphasize is that along with the misconceptions some correct concepts were found (though some of them were used only in isolated situations). These correct concepts were useful for planning and developing the lectures:

— Everyone recognized that objects fall on earth due to gravitational attraction.

— Eighty percent explained that some celestial bodies may not come to rest because they are too far away from any gravitational field.

— Forty percent thought of gravitational attraction as the cause of curved trajectories of celestial bodies.

— Fifty-eight percent recognized there is gravity on the moon.

— Everyone identified correctly the direction of velocity in two dimensional motion.

The first goal of the lectures was to present motion as something natural, using celestial examples [16]. I began with a discussion of the concepts of mass (as amount of matter), volumes and densities using large values with stars and small ones with atomic particles. In order to make motion appear natural, I followed this with a description of trajectories, mean velocities and instantaneous velocities using the same examples already employed.

The next step was to bring the students' concept of force to the fore. I asked them to identify forces acting on the bodies whose trajectories had already been discussed, and to explain how those forces influence motion. Most of the students thought about force as something analogous to the concept of momentum. At that point I made it clear that the "concept" they were really thinking of, was that of momentum, and I suggested not to use the word force until it had been defined later. Once we had identified "spontaneous momentum", the students analyzed the

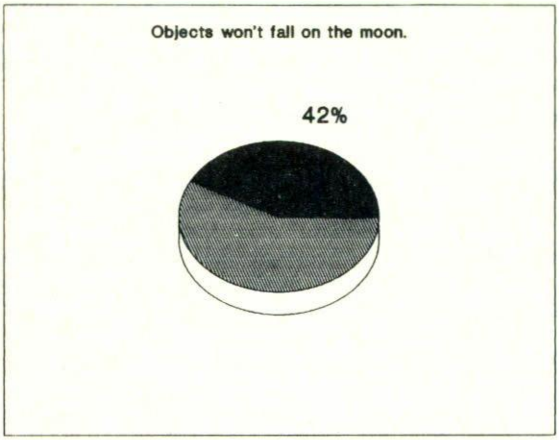

FIGURE 1.

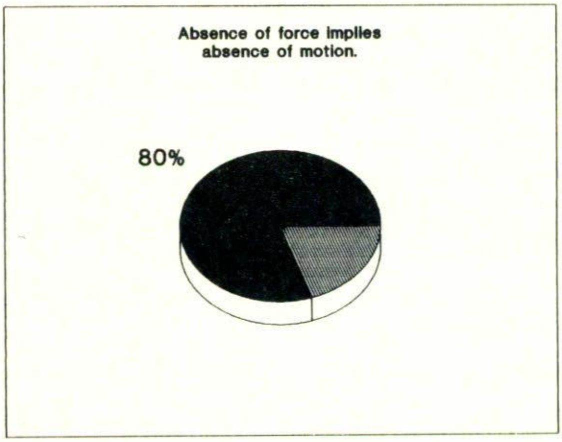

FIGURE 2.

examples again, replacing the word force with momentum. Then we described other examples of motion but, this time, using everyday phenomena like kicking a ball, an inclined plane, a person running.

The questions students were asked were: "How can we stop an object?" and "How can we decrease its momentum?". At this point the requirement of the moving object interacting with at least another body appeared spontaneously. Mass was the first attribute students thought necessary in order for the second object to be able to stop the first one. After the students observed collisions between objects of different and equal masses, using pendulums and marbles on smooth surfaces, they arrived at the conclusion that the second object's speed was important too; so a combination of speed and mass was required. Using these elements momentum was defined.

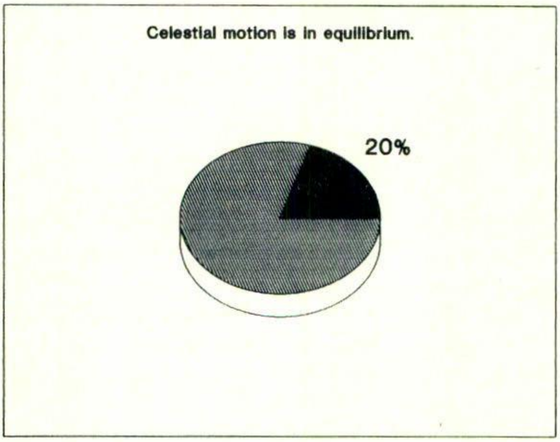

FIGURE 3.

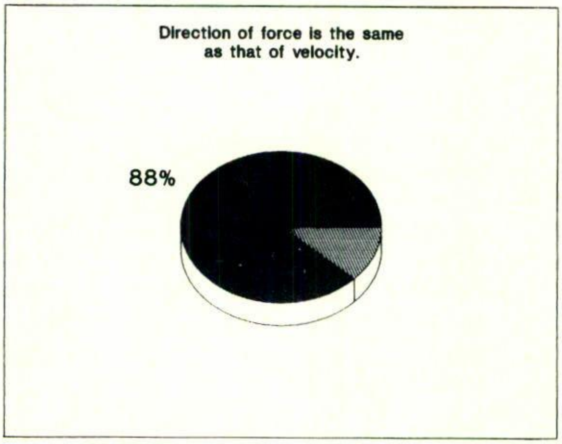

FIGURE 4.

The next question was: "What happens with the first object's momentum? Is it completely transferred to the second body?", or "Is there a loss somehow?". Almost half of the students believed momentum disappeared little by little. The rest of them thought momentum was conserved and so had to be transmitted. Students had the opportunity to deliberate in groups of four, and they experimented again with marbles and small balls. Furthermore, celestial movements were again analyzed, as well as other situations not discussed before. All groups reached the conclusion that momentum had to be transmitted, not created or destroyed; however none of the students said anything related to a conservation law.

The conservation law for momentum was introduced and then Newton's First Law was stated: if momentum doesn't change the velocity is constant; if a body changes its momentum it is then inferred that it is interacting with at least one other body.

Finally the concept of force was defined as the change of momentum in time then, in order to visualize the direction of the force, students had to do several exercises drawing the momentum vector along different paths, and then drawing its change for two neighboring points; and lastly Newton's Third Law was deduced from the conservation of momentum. Afterwards the concept of acceleration was defined and we were able to write Newton's Second Law in the traditional way. Additionally, gravitation and Coulomb's Laws were introduced.

We went back to the same examples and they were analyzed using Newton's Laws. New cases were offered in order to apply gravitation and Coulomb's Law. Some examples of everyday experiences were very useful in analyzing the role of time in Newton's Second Law: Why, when we jump down, is it better to bend our knees when touching the ground? Why, when we catch a hard ball, do we move our hand backwards? Why, do we feel less pain when we catch a soft ball? Why do some balls hit the floor harder than others?. The analysis of all the examples described above were done using the so called "conceptual mapping" [17,18].

At the end of the semester, it was decided to apply a test already used at the National University in Mexico City with two samples of students: 108 freshman and 44 sophomore science students [19] (we will call the samples UNAM1 and UNAM2). The test contained eight questions. Three or four answers were given as options for each question but only one was completely correct. Students supposedly had one hundred pesos to bet on each question and they could bet this amount on whatever answer they thought right, or they could divide the money selecting more than one option. Each proposed response took into account some of the students' most common misconceptions. The questions described the following phenomena:

A cat wakes up and starts moving; a pendulum follows a circular path; an object moves with constant speed on a closed path; a communication satellite revolves around the earth; a book is pushed on a table, moves and comes to rest; a boy tries to push a big box but in spite of his efforts the box won't budge; and the trajectory followed by a baseball.

Each of the answers involves more than one concept, so I have classified the individual concepts as follows (the first eight are correct conceptions):

1. A living body needs, as does any other body, an external force in order to move.

2. The net force acting on a pendulum whose path is circular is directed to the center of the circumference.

3. The net force acting on a body with constant velocity is zero.

4. The net force acting on a car following a curved path is directed to the center of the curve.

5. The curved shape of a satellite's path is due to gravitational attraction.

6. An object, moving on any surface on earth, stops because of friction.

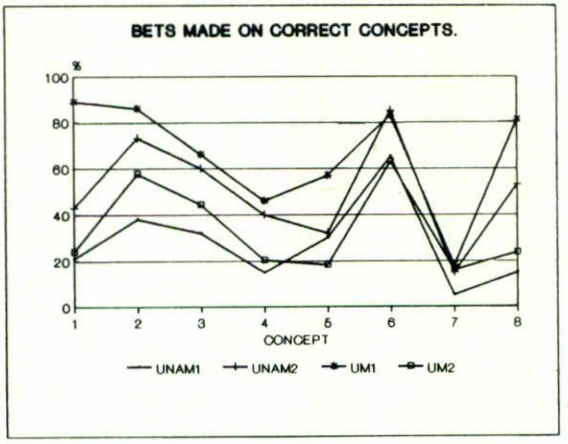

FIGURE 5.

7. If we try to move an object and it won't move, this is due to the opposite force the floor exerts on the object.

8. The forces acting on a projectile are its weight and air resistance.

9. Friction is greater than the force applied when the object won't move.

10. Objects on earth always come to rest because they lose force.

11. Force has the same direction as velocity.

12. In order to maintain the speed of an object, a force must be applied.

13. Satellites maintain their closed orbits because centrifugal force cancels gravitational attraction.

14. Satellites maintain their closed orbits because their trajectories are "natural".

Results obtained from biology students at the University of Michoacan (UM1) were compared with those obtained at National University of Mexico (UNAM1 and UNAM2) and with another 31 students who had finished their first semester in the school of biology and had passed their general physics course (UM2).

Figure 5 shows the average bet made on correct answers in each sample.

Roughly, results are in favor of the proposed strategy. Significative differences were found at the 95% confidence level between UM1 and UNAM1 in seven out of the eight correct concepts (only concept number 6 didn't show significant difference). Between UM1 and UM2, differences statistically significant were found in five out of the eight correct concepts namely: 1, 2, 4, 5 and 8; and between UM1 and UNAM2 in concepts 1, 5 and 8.

Figure 6 shows the average percentages of bets on misconceptions, numbered from 9 to 14. Significative differences at 95% confidence level were found between

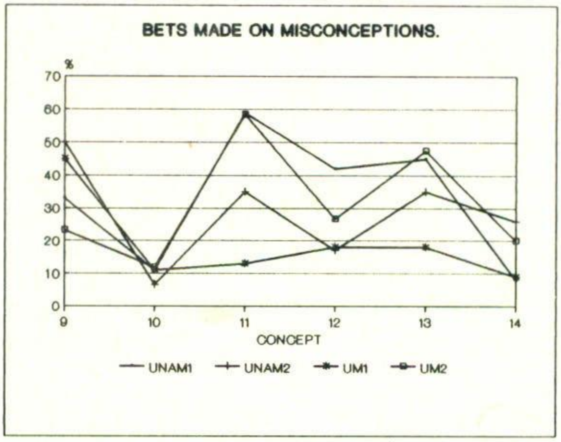

FIGURE 6.

UM1 and UNAM1 in concepts 11, 12, 13 and 14; in concepts 11 and 12 with UM2 and in concept 11 with UNAM2.

About correct concepts, the main differences in the samples were found in numbers 1, 5 and 8, namely: internal forces cannot produce changes in overall motion; satellite orbits are due to gravitational attraction; and, the forces acting on a projectile are due to gravitational attraction and the presence of air.

As seen in figure 6, there is no difference in the results with respect to misconceptions 9 and 10 namely: friction is considered to be greater than applied force, and objects tend to rest because they "lose force"; however the high percentages of bets made in favor of misconception 9 stand out. It seems that the students do not really think of friction as a force but rather as a kind of potential obstacle; this misconception may be related to the model that students hold of static forces.

After the application of the test all students were interviewed again in order to explore more closely the misconceptions found. Relevant results were that 40% of the students who had recognized the role of force in circular motion said that eventually, over a long period of time, celestial bodies could fall or collapse. However, they didn't justify this affirmation imagining a force opposite to motion, but rather by saying that this was a consequence of the force of attraction, which little by little would pull the objects gradually closer. This interpretation maintains the idea that rest is in the end the final state, and reveals a misunderstanding of the independence of the tangential and centripetal components of velocity.

Several studies report that between 20% and 75% of students hold misconceptions about the concept of force; among these, the beliefs that a force is needed to maintain uniform motion and that the direction of force is always the same as that of velocity, stand out [20,21,22,23]. The proposed strategy seems to be specially useful in dealing with misconceptions related to the direction of force, Newton's first Law and the differentiation between interaction forces and the so called pseudo forces. In general, the bet made in favor of correct concepts was between 46% and 89%, and between 9% and 18% in favor of misconceptions.

Finally, I just want to say that perhaps the most important justification of this research is the translation of some theoretical ideas into practice. Although the results presented come from a small sample, case studies have proved very useful in studying alternate concepts. It might be valuable to probe the suggested strategy in other contexts within the teaching practice, not only using experimental groups but also average classroom situations. Putting curricular innovations to operation under normal classroom circumstances presents serious difficulties within the context of teaching practice, perhaps greater at elementary school level [24,25] though not insignificant at high school and university levels.

It should be evident that effective teaching being careful of misconceptions requires more effort and considerable skill and preparation on the part of the instructor, and though mastery of the subject matter is necessary, it is not sufficient.

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16. We have observed, working with ten-year old rural children that the problems they have when trying to infer Newton's First Law from everyday experiences are not easy to overcome. The step between understanding that a body moving on a surface with little friction will stop after the same one moving on another surface with greater friction, and understanding that in the absence of friction it won't stop requires a great deal of abstraction. We have tried to explain the first law using celestial bodies and at that level it seems to work better than using terrestrial examples. A brief description of the project with rural children can be found in: S. Jara-Guerrero, "Hacia una educación científica", *Ciencia y Desarrollo* No. 72 (1987) 67–75.
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Resumen. Se presentan los resultados de una experiencia docente con estudiantes universitarios de primer ingreso. La estrategia utilizada tuvo como finalidad fundamental el tratamiento de los errores conceptuales más frecuentes de los estudiantes. El objetivo principal de este trabajo es mostrar un intento por llevar a la práctica algunos resultados teóricos de la investigación en enseñanza de la física.