Commentary

Why Is Physics Difficult? Some Reflections About the Cognitive Bases of Learning and Teaching Physics

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The study of physics is generally considered more difficult than that of mathematics, probably because the former is not a "deductive" discipline, even if it is often presented, at least in high school, as if it were a branch of mathematics. Does the difficulty lie in how it is taught or are there inherent difficulties in its learning?

First of all, it must be borne in mind that physics teaching (in universities and high schools) is only minimally based on a scientific approach, and largely based on little-verified practices.

Perhaps as a consequence, students often seem to behave in a "schizophrenic" way: they are able to solve the physics problems, when they are presented in formal and mathematical terms, but they radically mutate their approach if the problem is even slightly changed, use "un-physical" approaches when the problem is formulated in "everyday terms", and the approach methodologies can change, depending on the context.

From this a certain uselessness in teaching physics derives. This is probably not true for physics students, who probably would learn the same even without the courses, but holds for other students. This feeling is confirmed by the results of the *Force Concept Inventory*, a test to measure how much Galilean physics is used to interpret everyday events. The test is administered before and after a high school or university course, and the performance increase is modest.

Researches on cognitive sciences suggests that the "errors" of students are due to generic mechanisms, which are also active in other contexts, whose knowledge could be very useful in teaching physics. In this article we try to highlight some of these processes, without claiming to be exhaustive or complete.

The aspect that we think is the most important, is that learning physics is actually largely made up of the "un-learning" of intuitive associations, or rather, of the contextualization of intuitive physics, which cannot be eliminated since, after all, it is what allows us to survive.

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A good percentage of colleagues, all with many years of teaching behind them, answered absently yes, except of course correcting their answer when we asked them if they were really confident about their answer (the force is the same in the two configurations, but in (a) it accelerates both the masses M and m). The difficulty of physics therefore does not have much to do with the study. Of course, it is necessary, but that's not all. After all, physics is based on a few laws, which must be mastered, with a learning mode similar to that used to learn the game of chess. As in the latter case, we must practice, to be able to apply the laws and their mathematical derivation in an intuitive way, but unfortunately for physics this is not enough.

Physics, unlike chess, is "too" similar to reality, and contrasts with the intuitive physics modules that all of us (animals) carry from birth, as well as contrasting with other cognitive processes that hinder the learning of many other scientific disciplines. Let's see below what they are and how (maybe) this situation can be remedied.

1. Introduction

Physics is hard! How many times have we heard this complaint from so many students. And how often we physics teachers have replied *it's not true, it's you who don't study enough ....*

Well, it is not so, or better, it is true both that physics is intrinsically difficult, and that it requires intense and continuous training. Instead, it is doubtful that traditional study is of great usefulness.

To highlight how intrinsically difficult physics is, we just want to mention an experiment we did on colleagues during a conference break. We showed them, in an informal way, the scheme of Fig. 1, asking whether the acceleration of mass M was the same in the two situations. A good percentage of colleagues, all with many years of teaching behind them, answered absently yes, except of course correcting their answer when we asked them if they were really confident about their answer (the force is the same in the two configurations, but in (a) it accelerates both the masses M and m).

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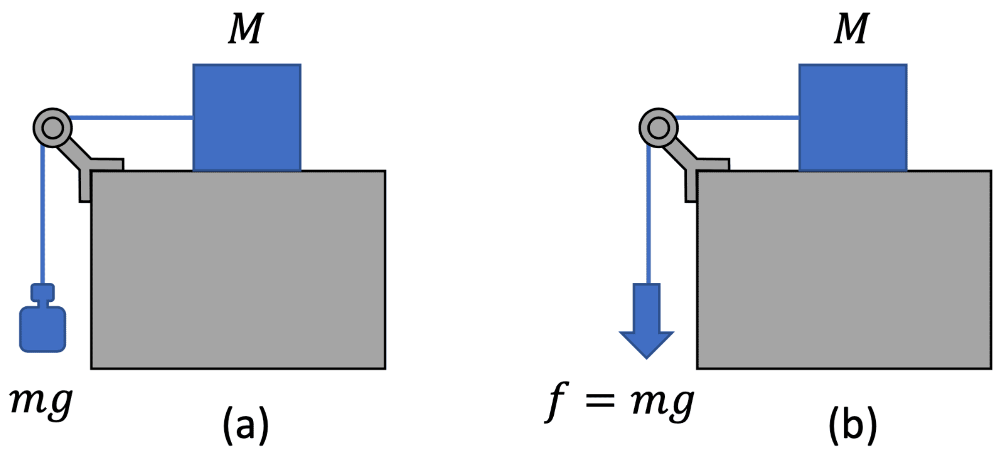

Figure 1. A simple test: is the acceleration of mass M in configuration (a) the same as in configuration (b)?

2. Intuitive physics

All of us animals (at least vertebrates, but likely also insects) are born with a basic physical-mathematical knowledge: the ability to count up to small integers (3-5), the notion of intuitive numerosity (distinguishing between 8 and 16 points), the impenetrability of bodies, the distinction between liquids and solids, and the distinction between animate and inanimate objects.

The typical experiment concerns the measure of the attention devoted to these phenomena. For example, one takes a child a few months old, and get him used to seeing sheets of paper with a certain number (say 8) of points drawn, with different arrangements. After the habituation phase, other examples of the same type with seven or nine points, or sheets with a very different number (for example 16) of points are presented. Children, when facing a different stimulus, stare at it for a longer time, showing surprise.

Similar experiments concern for example groups of 3 objects that are first shown, then covered and then revealed. If the objects have become two or four, the child shows surprise. In this way we can determine that children of a few months can "count" up to five, or distinguish very different numbers, expect solid objects to not interpenetrate, etc.[1].

These experiments can also be performed with other animals, for example a cat that sees three mice entering a hole and two coming out of it, puts itself in wait for the last one, something that does not happen if six mice enter and five come out.

In particular, many experiments have been done with chicks that have just hatched, which are very interesting experimental subjects since they are born "adults", with good mobility but little direct experience of the world. Moreover, the chicks are predisposed to get imprinted by the first mobile thing they see, and to follow it (with their eyes if they are prevented from moving). In this way experiments can be performed on the physical "expectations" of the chicks, for example that a screen that is too small cannot hide a large object, and so on[2].

With the insects obviously the experiments are different, but it is known that some wasps can count the number of paralysed caterpillars that they store for each egg, and that bees can be trained to distinguish between groups of different number of points[3].

One of the features we are most interested in here is that of intuitive physics: children and chicks expect heavy bodies to fall down, a ball to roll for a while and then stop, and so on. That is, inanimate bodies obey the "everyday physics", which vaguely resembles Aristotelian physics[4]. In fact, as noted by Rovelli, Aristotelian physics is a correct description of motion if it takes place in a viscous medium, just as it normally happens[5].

The evolutionary reason for this intuitive "physical module" is probably associated with the need to quickly distinguish between inanimate, non-dangerous objects and animated objects, to be kept under control.

The exact definition of intuitive physics is still under study, but some aspects are clear:

- Solid objects do not split spontaneously into two or more parts .
- Solid objects do not interpenetrate. If one places a sheet on an object, it is expected to produce a bulge. Conversely, a bulge shows that there is something below.
- Objects continue to exist even if they are not seen, when they are temporarily hidden.
- If not held by below or suspended, objects fall downwards.
- Heavier objects fall faster than light objects.
- Objects move in the direction of the force applied to them.
- In the absence of active "motors", inanimate objects stop after a while.
- Forces are exerted by active (living) subjects in an intentional manner.
- All effects are linearly related to causes if it is possible to perceive the quantity (double cause causes double effect), otherwise they are analogical (the effect is only qualitatively linked to the cause).
- Always refer to the typical case, not to the extreme ones.

Some of these elements are not peculiar to physics, but can also be identified in other contexts. For example, Ramachandran has developed a theory of neuroaesthetics (the cognitive bases of aesthetic and artistic experience) starting from principles of simplicity, for example that a too particular point of view (like an exactly symmetrical landscape) is unnatural, that an object partially hidden is probably composed of a single piece, and so on[6].

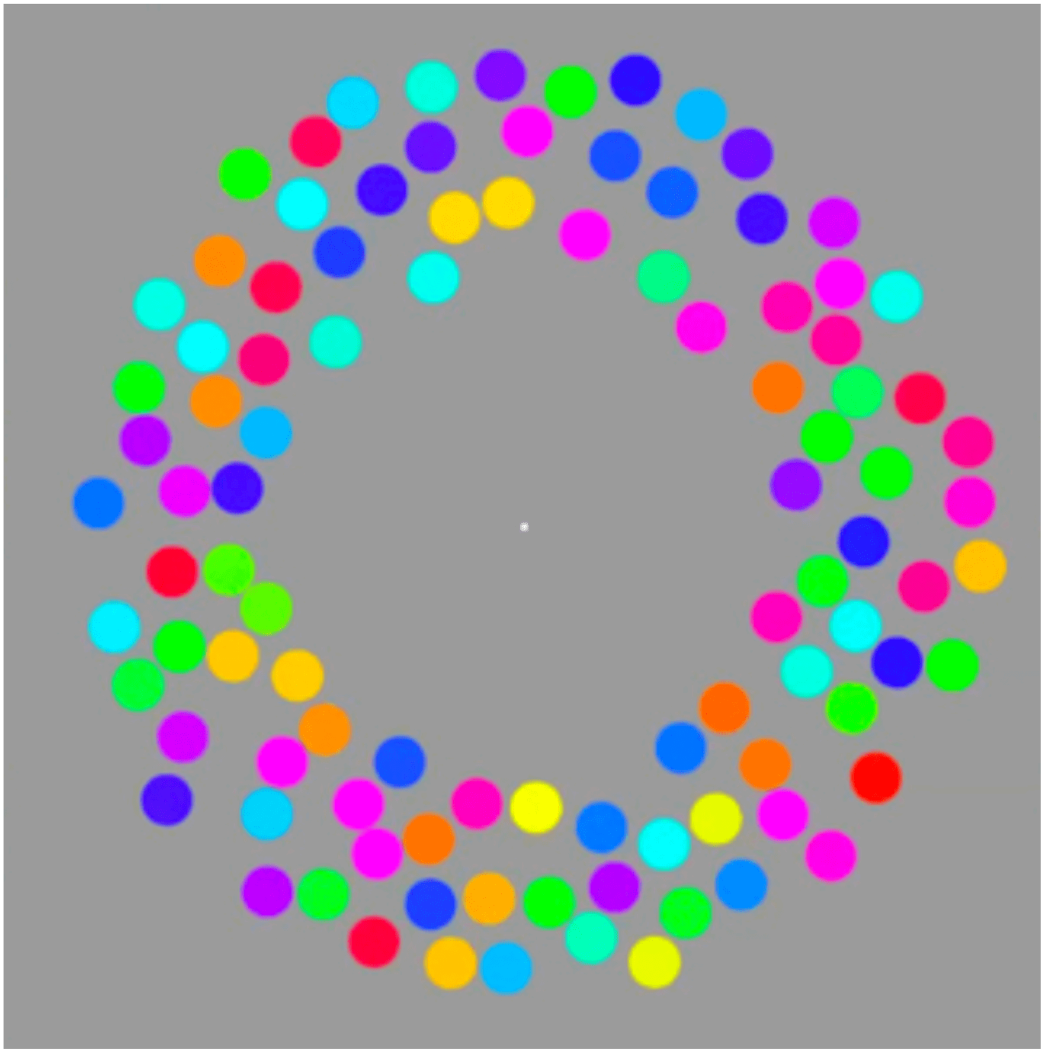

Figure 2. Motion silencing[7], see the video at https://youtu.be/IjMVsTFVX10

3. The dual process theory of thought and cognitive heuristics

An aspect to keep in mind to analyze the characteristics related to the interpretation of physical phenomena is that we can distinguish two modes of thought, called fast and slow, intuitive and deliberative, associative and rule-based, or simply System 1 and System 2[8].

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System 1 is unconscious, analogical (not able to count, except when dealing with small numbers or by means of the intuitive numerosity), fast, always active. It is the system that allows us to perform everyday tasks, as well as, after training, perform fairly complex tasks such as driving a car and responding emotionally to noise, etc. System 1 is based on the concept of "heuristic", that is, a stereotyped and effortless answer, simple and (generally) effective, even if not able to guarantee a normative response.

System 2, on the other hand, is deliberate, slow and tiring. It monitors System 1 activity inhibiting, if necessary, the automatic response of the latter. System 2 is also involved when System 1 cannot solve a situation, for example because one has to use a non-linear rule such as "if ... then", or to make a complex calculation (i.e., solving an integral). If System 2 does not have sufficient resources (for example, in time-constrained tasks), we rely on System 1 solution, even if it is perhaps wrong. Since using System 2 is tiring, we often adopt the response proposed by System 1 without making checks.

For example, the wrong answer to the test in Fig. 1 is a classic example of a heuristic: *ignore differences and anchor to what you know*.

Another simple example is the following: *At your preferred sports shop there is an exceptional offer: a ping pong racket and a ball at only 1.10 E. If the racket costs 1 E more than the ball, how much does the ball cost?*

Even those who are more inclined to do the calculations, feel within themselves a little voice that says "10 c, 10 c, 10 c ..." It is System 1 that does not know how to do the calculations and calls the system 2, suggesting however: *together they cost one and ten and you have to take away one, remains the ten...* .

These heuristics are at the base of so many "errors" encountered in physics tasks, for example, a problem concerning composite motion is the following: *a runner runs a length $d = 500m$ starting and arriving with zero speed, first with a uniformly accelerated motion with acceleration $a_1 = 2m/s^2$ and then with a uniformly decelerated motion with acceleration (negative) $a_2 = 3m/s^2$. Find the time needed.* A simple approach is *Given that the accelerations are not very different, let's say that it takes half the path with an acceleration and half with the other. Or since $2 + 3 = 5$, he will make the first $200m$ with acceleration $a_1 = 2m/s^2$ and the other 300 with deceleration $a_2 = 3m/s^2$.*

It must be kept in mind that the System 1 is composed of many processes, some always active, others called "in action" in chain. For example, a process that is always active is related to the attention to movement: if something (such as a mouse) moves, even outside the conscious visual area, the attention is immediately directed to the agent (the "tail of the eye"). Likewise, eyes are actively sought-after elements, even outside the conscious visual area: everybody happened to have the feeling of being observed, and, turning abruptly, discovered someone staring at him. This is not a "sixth sense", but only an unconscious process, which analyze the environment, for example using saccades[9], which are not presented to the conscious part.

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Most of the processes of the System 1 are chain activated by other “schemes” or “scripts”. This is particularly evident in the visual system: the amount of information coming from the visual apparatus is too large to be processed (at least consciously), so it is brutally filtered by unconscious processes before being passed to the System 2. A fine example is given by the “change blindness” or “motion silencing illusion”, in which a pattern that changes color and simultaneously rotates cannot be completely acquired, so the brain simply “rotates” the pattern already in memory, silencing the changes[7].

If we are then engaged in a particular task, like searching for something or following some animated action, this filtering is even more accentuated. So, if we focus on finding a pattern (house keys, glasses), we can pass in front of the object without “seeing” it just because we have recently changed the keychain, or ignoring even conspicuous objects in the scene (“selective attention test” or “the invisible gorilla”[10]).

While System 2 is serial, System 1 is parallel, which means that more patterns, even contrasting ones, can be activated at the same time, and also call System 2, as long as this does not lead to a conflict. This activation leads to “schizophrenic” behaviours, as revealed by interviews[11] and also by many oral exams: students can support a concept and immediately after the opposite concept, depending on the “stimulus” received.

But this is also the basis for learning physics: since we cannot eliminate the intuitive physics module, we can, however, train patterns that practically implement the script “eye that the fast response is probably wrong, we hear that System 2 says ”.

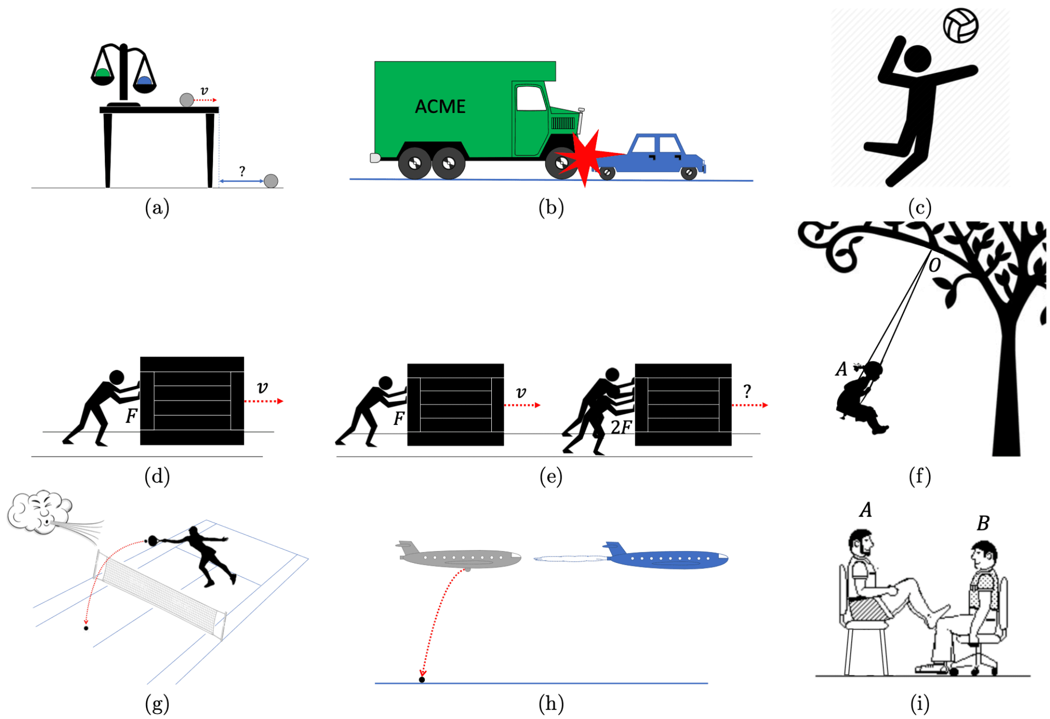

Figure 3. Some of the images accompanying the "Force Concept Inventory" test in the UNIFI version.

4. The force concept inventory

The "Force Concept Inventory" is a widely used tool to highlight the shortcomings of basic mechanical knowledge of students, both at the secondary and university level. It is a set of quizzes on kinematics and Newton's laws, formulated in an everyday language[12].

The test aims to probe the knowledge of accelerated motions, falling bodies, force effects and Newton's third law or action-and-reaction. Here are some of the most common errors (which are not always the majority, at least for UNIFI students):

- The force is confused with inertia: an object moves until it is "pushed" by a force, then "returns" to its natural logo, to put it in Aristotelian terms (Fig. 3c, 3f, 3g).
- The forces cause displacements in the direction in which they are oriented and vice versa.
- The heavier bodies fall faster, but they lose the initial speed faster (the heavier ball arrives first on the ground, but less distant when it falls from the table with a horizontal initial speed, Fig. 3a).
- The points of view are confused: a ball falling from an airplane, seen by a stationary observer, goes "back" not only with respect to the plane (due to air friction) but even with respect to the starting point (Fig. 3h).

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- To move, even at a constant speed, the force must be greater than the resistance (Fig. 3d) and if the force is increased the limit speed increases, (Fig. 3e). The problem here is that the friction resistance does not increase with the velocity, differently from what happens in fluids.
- The same problem (the motion on a horizontal plane) can have different answers depending on the orientation.
- The third principle of dynamics is the least understood: the force is proportional to the potential damage (Fig. 3b) or is connected to intentionality (Fig. 3i).

As pointed out by Rovelli, many of these "misconception" are very similar to the Aristotelian conception of physics, i..e., they are consistent with the experience of the motion of objects in a highly viscous fluid[5], which would explain why heavier objects go faster (and intuitively they are "more attracted" by the Earth), so that motion is in the direction of force (speed and kinetic energy are quickly dissipated), because a limit speed is always expected, proportional to the force[13].

In the next Section we will discuss the aspects related to the embodiement, which allow to explain other errors related to forces. However, what must be emphasized is that this test is generally offered both before and after students take a course in physics, and after they have passed the exam. Well, years of experience show that the increase in the test score is generally close to 15% -25%, both at high school and university level. Only if the topics of the course are discussed among peers or with the teachers, the percentage of improvement rises to almost 50%[14].

In the year 2018-1019 the test was administered, only at the beginning of the course, to various students of about 30 undergrad courses at the University of Florence, collecting almost 300 responses (the majority in engineering courses). Despite the fact that 47% comes from a scientific high school and 30% from a technical institute, high schools where physics is studied in depth, the distribution of the score, shown in Fig. 4, it is not encouraging, the average is only 10 points out of 30.

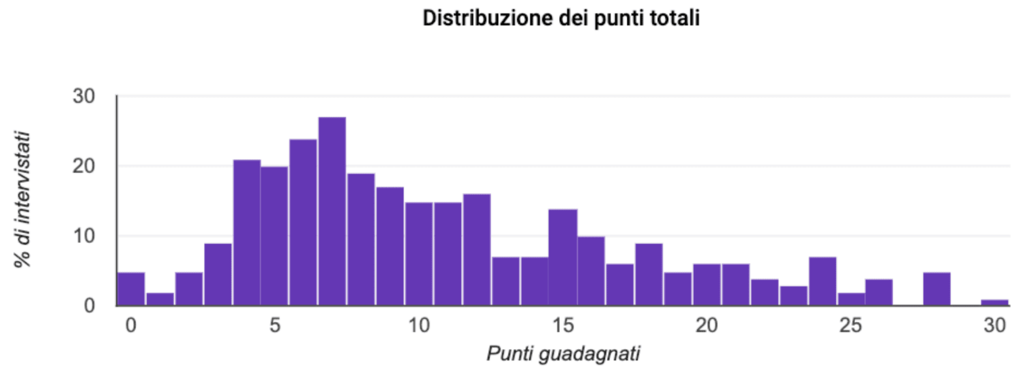

Figure 4. Score of “Force Concept Inventory” test at the University of Florence. The maximum score is 30 points.

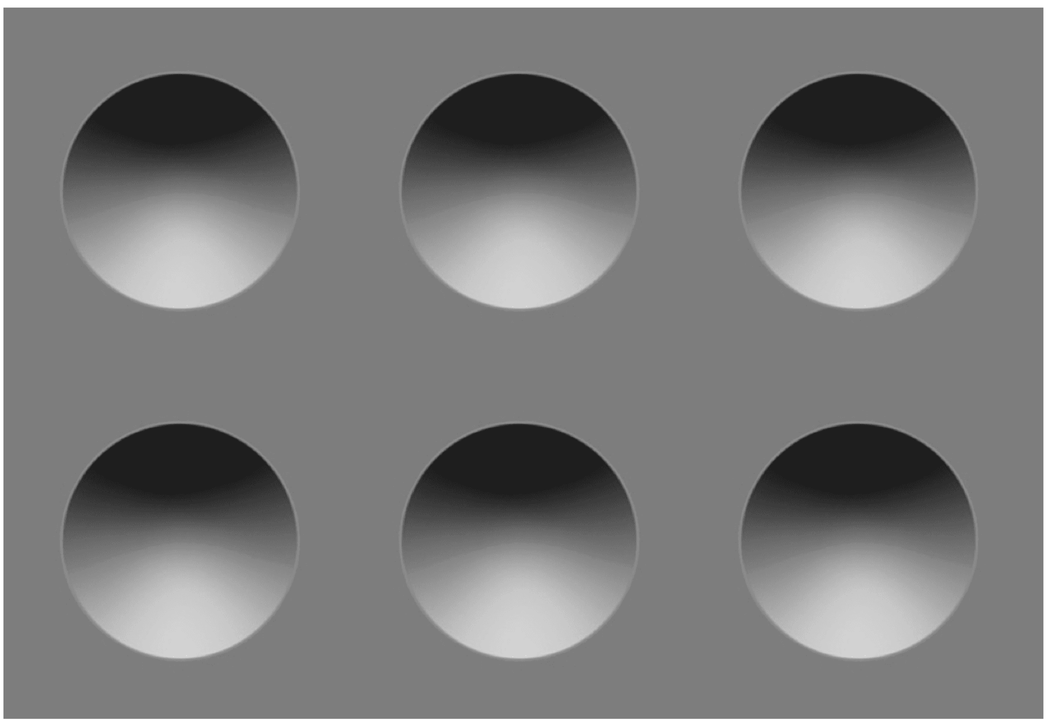

Figure 5. The illusion of the "muffin pan": the bumps and hollows switch places when the figure is turned.

5. Embodiement

Many of the problems related to the learning of physics have to do with the confusion of terms, including in particular that of force. We are linked to our body experience, and for us the force is linked to muscular effort. Furthermore, as shown by the research on mirror neurons[15], we exploit the "mapping" of actions on our body to understand the intentionality of an observed act. Therefore, it is not surprising if we instinctively connect force to intentionality, so that if we see one student pushing another by pressing his hand on his back or shoulder, we attribute the force only to the first. Conversely, if two students push each other by pressing the hands of one against those of the other, then the force is attributed to both.

Another particularly important element is linked to our habit of seeing the world vertically, with the light falling from above. This for example causes us a deep feeling of three-dimensionality in images that are in themselves two-dimensional, like the one represented in Fig. 5. If the image is turned upside down, the grooves turn into protuberances, since we expect the light to come from above.

Finally, a very interesting aspect is linked to the right-left scan, which we instinctively associate with the passing of time. One might think that this association is linked to the European direction of writing, but experiments with chicks show that even in this case a container containing food, which in the training phase was placed in a certain position "going away" from respect to the subject, is made to correspond to the container placed in the same position from right to left, when the row is presented in the "horizontal" direction[2].

6. The illusion of explanatory depth and the knowledge illusion

A crucial aspect that influences the study in all its forms (and that can probably be traced back to the influence of System 1 on the System 2) is the illusion of explanatory depth and the knowledge illusion[16]. If one asks a subject how much he/she estimates his/her knowledge on some technological aspect used every day (or a political hot topic), for example on how the toilet flush works, it is likely that the answer is very positive. When the subject is then asked to accurately describe the functioning of the system in question, he/she realizes his/her greatly overestimation if own knowledge.

This obviously also applies to exams. If one asks a student how much he/she estimates his/her marks on a written assignment just consigned, it is likely that the expectations are much higher than the actual mark. Moreover, this also happens to us teachers: faced with the prospect of spending a few hours preparing the lesson, we often think "I have already done this lesson last year, I am sure I remember it" with the implicit assumption that the saved time is more pleasantly used for something else.

The illusion of explanatory depth is strictly related to the knowledge illusion. The latter consists in not distinguishing between what we know as individuals and what we know as members of a community (that is, what the people around us know), hence the overestimation of individual knowledge. In fact, we humans tend to consider the knowledge of the group as "ours". A critical variable of this phenomenon is the

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accessibility of the knowledge: we are victims of this illusion if people around us are accessible (or if they are willing to share their knowledge with us). When a subject is told that scientists now know everything about the functioning of a cell or a nuclear reaction (without giving any further details), and then he/she is asked to estimate his/her own knowledge about the object, we observe higher scores than in the case where the subject is told that the scientists have understood everything but cannot share their knowledge because it is covered by a military secret.

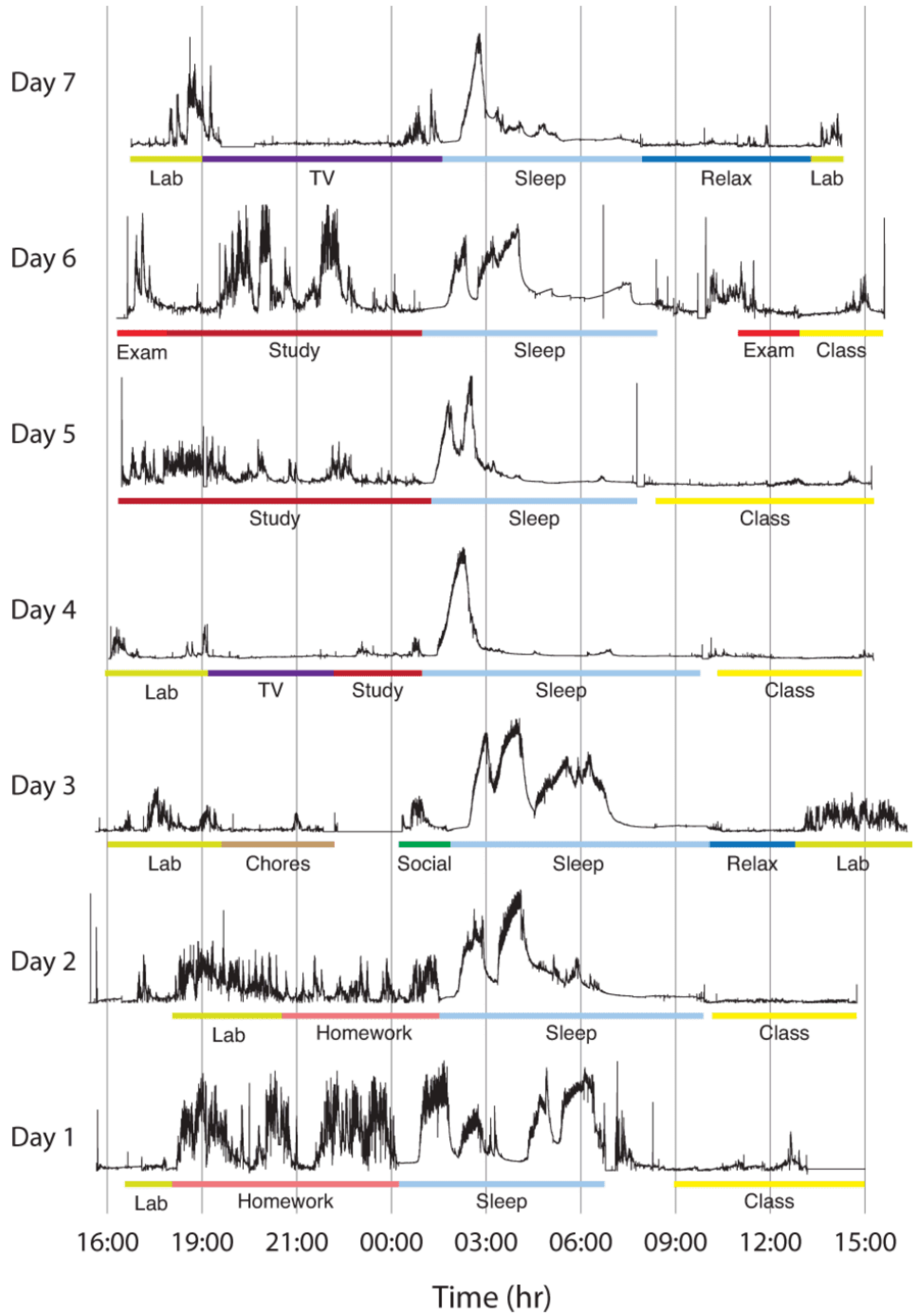

Figure 6. Monitoring a student's brain activity level during a week[17].

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7. Attention and reflection

A little considered aspect in the modality of supply of knowledge is then the mechanism of attention with respect to reflection.

To begin with, not many studies have measured the level of attention during a lesson, which would allow to better calibrate the breaks, or even to modulate the lesson by inserting elements of surprise. But the most important aspect concerns the way a lesson is used.

As you can see in Fig. 6, the Autonomic Nervous System (ANS) activity of a student (or any other person) measured by changes in skin conductance at the surface (electrodermal activity, EDA) is very varied. EDA reflects sympathetic arousal associated with emotion, cognition, and attention. The system is very active during study, homework, social and relaxing activities, even sleep (indeed, it is one of the periods of greatest intensity). The only moments when the activity drops close to zero are when one watches the TV and ... when he/she is attending a lecture.

In fact in these two cases we are in a “absorption and memorization” mode, in which there is no space for reflection and information processing. As Mazur points out during his seminars, the most intelligent question a student could ask during a lesson is “Professor, could you shut up for five minutes? I would like to think about what you just said.”

It would be very useful to be able to understand when to interrupt a lesson to let the students think. From this point of view, it would be much better to deliver the lesson in video, so that the attendees can stop it whenever they want. But on the other hand, the illusion of knowledge (and the consequent stimulus to follow the lesson) works only when one participates together in a common activity.

8. Peer instruction

A possible solution is to completely overturn the teaching scheme. After all, if the information processing phase is the one in which we discuss, and if the delivery works better on video, why repeat, year after year, the same show (the lesson)? Perhaps it would be better to dedicate the hours in class to the discussion, inviting students to read up on their own (or in groups) the book or using a recorded lesson.

These are roughly the reasons that led to developing the concept of the “flipped classroom” or “peer instruction”[18][19][20][21][22][23]. In this modality, the class is the place for discussion and verification. For example, one can divide the students into groups, and pose them a problem that must first be solved individually, and then discussed in the group, trying to arrive at a common answer (and the right one). Since the mark of the test derives from a combination of of the individual and group responses, it is convenient for everyone to be convinced by those who demonstrate that they have obtained the answer following the correct practice.

The peer instruction method certainly has a very interesting aspect. As pointed out by Sessa[11], the students do not actually follow a wrong theory in an organic way, as could be the Aristotelian or the medieval one[4], but rather a heterogeneous set of concepts, prompted by the narrative context (heuristics, schemes). It is rather difficult for a teacher to be able to "divine" these "original" interpretations of physics, and therefore to counter them in order to weaken their activation. Conversely, the best teacher for this purpose is the student who has just figured out how to use the right method, but is still quite "fresh" in ignorance (so to speak) to understand what is the origin for the companion's error.

Unfortunately, peer instruction is not easy to apply in our university system, with classes of hundreds of students and few tutors. A possible solution could be (in the experimental phase) to ask the students to answer questions in an open form, in order to "capture" the heterogeneity of the processing processes used, and then classify and use these answers in multiple-choice quizzes, to be delivered immediately after (or during) the lesson using the beloved (by students) mobile phones or clickers.

Figure 7. The famous scene with Luke Skywalker's trained by Yoda in the "Return of the Jedi".

9. Physics demonstrations and the magic

Finally, it is important to emphasize the role of "demonstrations" or physics experiments. Unfortunately, in general we have neither the time nor the opportunity to bring students into the laboratory, but this does not justify the predominantly deductive-mathematical approach generally used in teaching physics.

This approach, which confuses physics with mathematics, leads on the one hand to disaffection with the first, which is seen as “a more difficult mathematics, with uncertain rules”, and then increases the distance between the physical concepts, learned in a rational way, and the “perception” of physics in the reality. As Mazur always says, often the students who carry out the Force Concept Inventory ask *should I answer using what you taught us, or as I do think it really happens?*.

From this point of view, the classic “laboratories of didactic experiences” are of little use, since they are too artificial and far from the experience of everyday life. As noted by many teachers, *we doubt that a demonstration can be effective unless it is performed in a context that helps and resolve conflicts between common sense and specific scientific concepts*[13].

How can it be remedied? First, using videos, found on YouTube or made specifically (even with a mobile phone), analysed for example using Tracker[24]. For example, one can analyse sport videos[25], or images/clips from movies[26].

Or one can perform simple experiments in the classroom, using everyday materials, so that students can easily replicate them at home[27][28][29].

In particular, it would be extremely important to compare the results of the calculations on a certain exercise, with the “physical” realization of the same exercise, so to confirm that the model used actually constitutes a good approximation of reality. For example, filming the fall of a body and verifying that the law it follows is, to a good approximation, a parabola, as described by physics. One can also perform measurements, in the classroom, with the mobile phone, for example using the phyphox application[30].

One of the ways that has proved to be particularly lasting in the students’ memory is to introduce the demonstrations as if they were magic tricks, associating a narration and surprising effects[27][31][28]. In this way it is also possible to carry out demonstrations related to the behaviour of fluids, a topic often overlooked and considered accessory, but which, as we have said, constitutes the basis of Aristotelian physics[5].

The idea of using the computer as a simulation tool, for example to integrate the equations of motion of a planet, perhaps using simple tools like NetLogo[32] is not to be overlooked.

Finally, I would suggest the massive use of drawings in solving problems in the classroom, to the point of proposing to solve problems only through graphics. To begin with, it would provide students with a way to verify the qualitative and semi-quantitative correctness of the elaborate, and it can also be very useful to avoid “barking up the wrong tree”.

10. Conclusions

The learning of physics is often perceived as an accumulation of notions and mathematical derivations. In fact, in very few books we find the highlight the methods to be used to deal with a problem, how to carry on experiments to confirm hypotheses, or the possible errors in which we can run into. In the case of physics the situation is even worse, given that the proposed concepts (and methods) conflict with the modules of “intuitive physics”, of probably geneticorigin, on how the world should be expected to behave.

Our cognitive system is only apparently rational: normally we use heuristic rules (called System 1), which are easy, effortless and automatic, instead of using System 2, the rational one, which is slow and tiring.

From this it follows that the most important aspect to keep in mind when teaching is that the learning of physics is in reality largely constituted by the “un-learning” of intuitive associations, or at least by their “contextualization”

We cannot eliminate the knowledge of intuitive physics, which is what helps us to survive, but, as teachers, we aim to “weaken” the automatic associations, promoting the onset of an “alarm bell” that says: *Pay attention that the solution proposed by System 1 is probably wrong. Examine the problem from many sides, study limit cases, make (or imagine) a drawing, simplify and throw away the superfluous....* An approach that even we teacher do not normally follow...

For further information (in Italian) see the wikibook Teaching physics[33].

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