Analizing high school students' problem solving through their personal epistemologies

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(Received 27 September 2013, accepted 25 February 2014)

Abstract

A case study is presented in which the epistemic aspects of three students' productions during problem solving are analyzed. These students address a non-instructional Mechanics problem. The theoretical framework adopted is that of Cognitive Resources, which assumes that students' cognitive activities are epistemicaly framed via the activation of epistemic resources. The analysis shows that students' epistemic frames can account for certain characteristics of their reasonings. Furthermore, the epistemic analysis offered gives insight into how they are able to carry out a metacognitive analysis on their own reasoning. Regarding the characteristics in these students personal epistemologies, these high-school students exhibit an epistemic sophistication compared to that of more advanced university students reported in the literature.

Keywords: Personal epistemologies, cognitive resources, metacognition.

Resumen

Se presenta un estudio de caso en el que se analizan los aspectos epistémicos de producciones de tres estudiantes durante la resolución de problemas. Estos estudiantes abordan un problema no instruccional de Mecánica. El marco teórico adoptado es el de Recursos Cognitivos, que asume que las actividades cognitivas de los estudiantes se enmarcadas epistemológicamente a través de la activación de los recursos epistémicos. El análisis muestra que los marcos epistémicos de los estudiantes pueden dar cuenta de algunas características de sus razonamientos. Además, el análisis epistémico ofrecido da una idea de la forma en que son capaces de llevar a cabo un análisis metacognitivo sobre su propio razonamiento. En cuanto a las características de las epistemologías personales de estos estudiantes, estos estudiantes de secundaria muestran una sofisticación epistemológica en comparación con la de los estudiantes universitarios más avanzados en la literatura.

Palabras clave: Epistemologías personales, recursos cognitivos, metacognición.

PACS: 01.40.Fk**,** 01.40.gb, **ISSN 1870-9095**

I. INTRODUCTION

In not few occasions, Physics Education Research has undertaken the study of students' epistemological beliefs about science as an attempt to better understand and accordingly address their difficulties in learning. [1, 2, 3, 4, 5, 6, 7]. On the other hand, researchers interested in how students build their ideas about the epistemology of Physics (also often referred to as "Nature of Science", or NOS), have found that engaging students in inquiry activities during school practice is insufficient to change most of their ideas about NOS [8, 9].

Based on a review of research on students' epistemological beliefs, and on students' inquiry practices (including some of the ones mentioned above), Sandoval [10] points out a gap between results offered by these two kinds of studies and expresses this gap in the form of a paradox: students' practices of inquiry appear to share much with science practice, and nevertheless, their expressed epistemological beliefs often seem hopelessly naïve. This author claims that the starting point to solve this paradox lies in the differences between practical epistemologies and formal epistemologies.

In the next subsections we will: briefly discuss these differences (Public vs. Personal Epistemologies), present our arguments to adopt personal epistemologies to study learning-related issues (Personal epistemologies to understand learning activities) and comment some existing work that follows the same trend (Some existing results on personal epistemologies); The next two sections outline the theoretical framework adopted and the setup of the study. Finally, results on students' epistemic sophistication are detailed in relation to their reasonings on the physical situation and on their own metacognitive reflection and the paper concludes with a discussion section.

II. PERSONAL EPISTEMOLOGIES TO UNDERSTAND LEARNING ACTIVITIES

We ascribe to Sandoval's [10] view that personal epistemologies, and not public epistemologies, are what should be focused on to better understand students' abilities as well as their difficulties in activities such as problem solving and inquiry. This author bases his argument on the revision of a great number of reports on the research of people's conceptions of NOS. His claim is based on two main issues.

First, as mentioned above, a person's epistemological conceptions are not stable and globally coherent, but rather fragmented, unstable and subject to context variations. This inconsistency across contexts has been reported by several authors [11, 9, 12]. Students' answers show inconsistencies not only when assessed through different instruments, but also at different times.

The second issue is precisely the difference between the set of ideas about scientific knowledge and its production that students appear to have about professional (formal) science, *i.e*. public epistemologies, and those about their own knowledge production in school science. This argument is similar to Hogan's [13] distinction between distal and proximal epistemologies. Her notion of distal epistemology is roughly the same as what we are calling public epistemology, and the term 'distal' connotes the distance of such ideas from students' own experience. Proximal epistemology, on the other hand, or the beliefs that students have about themselves as science learners, are more likely to influence their approaches to learning than distal epistemological ideas. Thus, in order to better understand students' approaches to learning, personal (proximal) rather than public (distal) epistemologies should be focused on.

Other researchers also agree that the focus should be laid on students' personal rather than public epistemologies [14, 15, 16]. Their reasons follow the same arguments: personal epistemologies are the ones involved in deciding (explicitly or implicitly) which is the relevant knowledge involved in cognitive tasks such as learning, problem solving, inquiry, etc. They are the means through which students answer the implicit question "what is this about? / what am I supposed to do here?" These practical or personal approaches to the construction of knowledge are much more informative to understand the characteristics of tasks such as argumentation, problem solving, inquiry, and learning in general. These are the arguments that we share and which lead us to adopt personal epistemologies as the lens through which to analyze students' productions while learning Physics.

III. SOME EXISTING RESULTS ON PERSONAL EPISTEMOLOGIES

The literature offers reports in which personal epistemologies have proven fruitful to understand students' learning activities. One such example is provided by Lising & Elby [17]. These authors analyze the productions of a student (pseudonym Jan). Their data come from Jan's problem solving sessions with another student and also from personal interviews. They show that Jan approaches the cognitive task at hand in two different ways. One of them is given the name of everyday/intuitive reasoning, as opposed to formal reasoning. When engaged in everyday reasoning, Jan attempts to make sense of situations as she would do in everyday situations, she calls upon her common sense and her memories of similar situations in the past when interacting with similar phenomena. When Jan exhibits a formal reasoning, she makes clear attempts to use formal tools such as formulas and physical concepts; the validity of these formal tools seems to be sustained solely on the authority of the source from which they were obtained. Beyond the characterization of these two kinds of reasoning, the authors are able to establish that Jan's difficulties in learning are epistemological in nature, and they can be understood in terms of a barrier between these two kinds of reasoning: they find that Jan reconciles ideas much less often when those reconciliations imply comparing an everyday reasoning with a formal reasoning than when those reconciliations occur between reasonings of the same type.

Hutchison & Hammer [18] present a report in which they show how university students in a junior year physics class frame their work in two different ways. The two framings are referred to as "the classroom game" and "making sense of a natural phenomenon". In the classroom game, the knowledge that is taken as valid is the one sanctioned to be correct by an authoritative source. Students' role in this frame is to reproduce that correct knowledge as closely as possible, *i.e.* they are supposed to deliver correct answers. The second framing they describe, on the contrary, is described by the authors as a more productive one, in which students are engaged in building knowledge as they try to make sense of a phenomenon. The valid knowledge in this frame can come from a variety of sources, such as observations, prior experience or instruction, and their main activity is to decide whether the ideas they build are coherent with what they already know. This work describes how teachers' interventions can nudge students into framing their classroom activity in more productive or unproductive ways.

Bing & Redish [19, 20] study the epistemic sophistication of advanced university students in what concerns the use of mathematics during physics problem solving. These authors aim at describing the epistemological component of students' evolving expertise. In the first of these reports [19] they show how a group of intermediate university students are "stuck" in a particular epistemic frame. Within this frame, the value of a given mathematical procedure is given by the authority from which the formulation is obtained; thus, they do not consider the physical meaning of the variables involved. These students persist on this frame even when the interviewer tries to hint them into a different framing. After recovering the "correct" formula from an authoritative source, they spend a great amount of time without noticing that the formula is not suitable for that problem in particular. In the second of these studies [20] the authors show how a group of students recover a "correct" formula (an integral for an expectation value) and based solely on its validity they execute a series of correct mathematical procedures. Since in their framing there is no attention to physical considerations, they do not realize that they have inadequately set the integration limits. In this frame, the validity of results is given basically by two factors: the authority from which the formula is obtained, and the correct mathematical manipulation. Since both these conditions are satisfied, the students are convinced that the problem has no solution: the integral they try to find has no solution with those integration limits. The way out of this dead end comes from a shift in their frame, incorporating an analysis of the physical meaning of the quantities involved. One of the students attempts to make physical sense of the computations they have been carrying out and realizes that given the characteristics of the potential at hand, the integral must be computed between different integration limits. These two examples show that epistemic considerations can inform teachers and researchers on why students can get stuck in inadequate, or sterile, solution paths. Also, it illustrates how a shift in their epistemic framing can result in a productive change in their solving strategies. The authors refer to this ability to shift their epistemic framing as an important component of students' developing expertise, and they call it epistemic sophistication. A more compelling example of epistemic sophistication is reported in that same paper [20]. In this case, it corresponds to a student who already held an undergraduate science degree and had spent several years in the work-place before returning to the university to study for another degree. The data from this student were obtained from an interview on the problems that had been the subject of a recent exam. The data showed that this subject was able to frame the task in three different ways, each of which is dominated by three distinct epistemic goals: to make physical sense of the equations, to recover correct information from authority, and to evaluate the internal consistency of the mathematical representation. What is interesting about this subject's epistemic sophistication is not only that he can frame the task in these different ways, but he can shift to a new frame without disregarding the previous one. This enables him to seek coherence between the conclusions he obtains in those different frames.

In the present study, we carry out an analysis of three students' solving session of a Mechanics problem from an epistemic framing perspective. We attempt to show that the epistemic sophistication reported by Bing & Redish in intermediate and advanced university students can be also found in students of a sensibly shorter academic trajectory such as the high school students in our case study. These 5th year students (approximately 16 years of age) exhibit an epistemic sophistication that allows them to address a problem involving a topic that had not been part of their instruction prior to the interview. We also discuss how these students' epistemic sophistication enables them to carry out a metacognitive analysis of what they do and do not know.

IV. A THEORETICAL DESCRIPTION FOR PERSONAL EPISTEMOLOGIES

In order to perform our analysis of students' personal epistemologies, we adopt the theoretical viewpoint given by the Cognitive Resources framework. This is the theoretical framework also used by Bing & Redish [19, 20] to study the use of mathematics in physics problem solving. It approaches cognition from a knowledge-in-pieces perspective, and assumes that people's cognition is the result of activating Cognitive Resources. An appealing characteristic of knowledge-in-pieces frameworks such as this one is that they incorporate a contextualized view of cognition in a natural way: resources are activated in a context dependent manner. This has two important implications. First, it allows to understand why students sometimes appear not to know things that they are reasonably assumed to know, or in other words, why they are or are not able to transfer knowledge from one situation to another (for a more extensive analysis on the impact of the knowledge-in-pieces framework on transfer see [21, 22, 23]). The second important implication is that this context sensitivity opens the possibility to analyze processes, and not just results of cognitive activity. That is, instead of focusing on the results of students' reasoning, they are more suitable to understand how students produce those reasoning.

In a first, broad classification, cognitive resources can be either conceptual or epistemic. Conceptual resources are what enable people to make sense of the functioning of physical systems. Epistemic resources, on the other hand, are activated to provide a control structure that allows people to give epistemic sense to the cognitive task at hand, in other words, the activation of epistemic resources provides an answer to the (sometimes implicit) question "what is this about"/"what am I supposed to do here?" [14, 24, 18, 25].

Since the purpose of our study is to analyze the epistemic component of students' cognitive activity, we will focus on the epistemic resources activated during a problem solving session. The central assumption in our work is that when confronted with a cognitive task, people activate a particular set of epistemic resources and that this activation constitutes an Epistemic Framing. As an example, consider the following example presented by Bing & Redish [20]. During a problem solving task, a group of students frames the activity as one in which their role is to deliver correct numerical results by means of valid mathematical operations. Two resources are activated to build up this frame: calculation and Invoking Authority. The first one, calculation, can be described as "correctly following an accepted calculation algorithm produces valid results". Invoking Authority implies that "information obtained from a recognized authority, such as the textbook or a teacher is trustable to obtain correct answers". Once activated, these resources dominate the epistemic framing during the solving activity.

Hutchison & Hammer [19] describe two different epistemic framings that occur within a classroom environment: "making sense of a natural phenomenon" and "playing the classroom game". Within the first framing, students are engaged in considering ideas and statements about knowledge that are built up from pieces of knowledge originated in diverse sources, such as previous experience, authoritative sources like teachers or textbooks, common sense, previous instruction, etc. What is characteristic of this framing is that subjects' main task is that of elaborating new knowledge and evaluating it by checking its coherence as compared to what they already know. This overall quest for coherence is what indicates the activation of the resource of "making sense" which dominates the frame.

When framing the task as a classroom game, students assume that their role is that of delivering correct answers. The resource that is activated to build up this frame is basically that of Invoking Authority. This implies that information is regarded as valuable and useful when it coincides with what the authority sanctions as correct. The epistemic criterion provided by this resource is what dominates the activity within this frame.

The present work offers an analysis of students' activities during a problem solving session, based on the characteristics of their epistemic framings. The framings that we will encounter are characterized mainly by the resources of making physical sense of a natural phenomenon and Invoking Authority, although they are not the only resources that will be described. The results will contribute to the understanding of students' cognitive activity during problem solving in two ways. First, the shift from one frame to another will inform us on why sometimes students appear to "know" things in one situation and not in another. Second, it will provide an interesting tool to grasp the epistemic sophistication of academically "young" students. In fact, the epistemic sophistication of the students in this report is comparable to the one reported in more advanced (university) students as in the case offered by Bing & Redish [20]. Finally we address the issue of how epistemic sophistication plays a decisive role in these students' ability to reflect metacognitively on their own productions.

V. THE STUDY

In this report we present a case-study analysis of three students' productions during problem solving. The participants are three high-school students in a 5th-year course (16 yr. old). The school is an institution that belongs to the Universidad Nacional de Córdoba, a federal state university in Argentina. Data were collected by means of a semi-structured interview. It consisted of a mechanics problem presented in a sequence, and students were asked to discuss their approach to its solution. The atmosphere was that of a peer interaction in order to favor their communication of ideas. Students agreed to participate in the interviews after a call made to them by the researchers and their Physics teacher.

These students' instruction prior to the interview had covered the topic of kinematics in one dimension, and in particular, the description of motion with constant speed and constant acceleration. The example of bodies moving vertically near the Earth's surface had been used to illustrate constant acceleration motion. Dynamics had not been a topic in their instruction, although they were familiar with the idea of weight as a measure of an interaction that pulls bodies to the center of the Earth.

Interviews were audio-video recorded and then analyzed. The analysis performed focused on the identification of the epistemic resources activated and the overall epistemic framing, in terms of those resources that dominate the framing. We focused on how students' reasonings were supported by particular framings, and also on the epistemic abilities that students exhibit. These, as pointed out by Bing & Redish [20] are a component of their developing expertise. Throughout the results we will also point out certain metacognitive actions enabled by this epistemic sophistication: students become aware of the limits of certain idealized kinematic models, they understand why they are changing their minds about the behavior of the physical system, and they conciliate two different descriptions of a system.

Two balls, a bowling ball and a soccer ball, are the same size but different weight. They are both released at the same time from a rooftop that is 4 m above the ground. Choose the right answer and give your reasons for it:

Upon hitting the ground the speed of the bowling ball is:

a) greater than
b) less than
c) equal to

the speed of the soccer ball

The acceleration of the bowling ball is:

a) greater than
b) less than
c) equal to

the acceleration of the soccer ball

The time it takes the bowling ball to hit the ground is:

a) greater than
b) less than
c) equal to

the time it takes the soccer ball to hit the ground

FIGURE 1. The problem discussed during the interview.

VI. RESULTS

We have chosen 5 excerpts to illustrate the nuances in students' framing observed during the interview, and to provide the basis for our analysis.

A. Framing the task as a sense-making activity

Immediately after reading the problem statement the three students (S1, S2 and S3) recall an episode in which a teacher had talked to them about an experiment in which a feather and a rock, falling in vacuum, did so at the same time and with the same speed. They clearly distinguish that episode from the present one, and the point is that their activity consists of seeking coherence between the present ideas and other things that they already know.

Interviewer: *Can you tell me what you're thinking?*

S1: *... some time ago, there was this teacher, not our regular teacher* [a substitute], *and she told us this story about someone who had done this experiment… with a feather and a rock…*

S2: (interrupts) *…a rock and a feather, in vacuum, and they both fell at the same time, and with the same speed… it's like… weight had nothing to do with the speed that they fall…*

S1: *yeah, but to do that, they had to do something special, 'cause if you drop… like, here, or anywhere, a rock and a feather, the rock is gonna fall first!*

S2: *and here* [in the problem statement] *it doesn't say if you have to take into account the friction with air… so we're supposing that there is air, and there is friction with air, it's not like, in vacuum, so they won't fall at the same time.*

S3: I *think they will… 'cause they have the same volume… and the same shape…*

Int: *So, are you saying that even if you take friction into account, it's the same for both bodies, because they have the same shape?*

S3: *well… yes, that's what I'm guessing… I mean… the bowling ball, it's got more mass, so maybe then the air won't affect it as much…*

S1: *but, if you have two balls, with the same shape, and one is heavier than the other…*

S2: (interrupts) *to me… the heavier one will fall first…*

S1: *right!*

Int: *and… why do you think that's how it is? Someone taught you that? you read it somewhere?*

S1: *No! We just KNOW because we've dropped a… two… bodies that are alike, but of different weight… and, well… the heavier one falls before the other one!*

S2: *... it's like we're backing up what we think with what we're studying.*

Physical Sense-Making is the resource that dominates the framing, because it can account for what they are taking the task to be about. The answer to the unspoken question "what is this about?" is precisely "this is about making sense of what would happen in that situation". A distinctive trait of Physical Sense-Making is that it does not place restrictions on the valid sources of knowledge. In this case, we see students evoking previous knowledge from previous classroom examples (*"there was this teacher who told us about an experiment"*), and from their personal experience (*"we just KNOW because we've dropped bodies that are alike"*). All sources of knowledge are valid as long as they can serve the purpose of providing elements to carry out the task of making sense of the situation. The fact that one of those sources is a teacher, an authoritative source, indicates that Invoking Authority has also been activated, but it is not dominating the frame. This resource is not guiding their reasoning, it is part of the framing because it feeds into their present sense-making.

B. Sense making as a fruitful framing: a useful analogy

So far, students are confident in the idea that, in the presence of air, the heavier ball will hit the ground with a greater speed. They arrived at this conclusion within a sense-making frame, in which they have analyzed the present situation in relation to their previous ideas of falling objects. The following excerpt illustrates how, as they attempt to make sense of the situation, they make an analogy. They recall a classroom example, in which two crowns were submerged in water in order to find out which of them was made of gold and which from a lighter metal. The analogy consists of comparing the case of two crowns of same size and different weights, submerged in water, with the present one of two balls, also of the same size and different weights, submerged in another fluid: air. This analogy allows them to validate their sense making reasoning. Also, this sense-making involves a description of the physical interaction between a fluid and an object falling in it. In any case, having the same size and shape, both bodies have to face the same resistance from the fluid. The body with the larger mass (and weight) will be pulled down with a greater force and thus arrive at the ground with a greater speed.

S2: *…the math teacher had brought up that example, with a crown… that this king wanted to know if it was made of pure gold, or if…*

S3: *oh… you mean that example… the two crowns were put in water, and they had the same volume, but gold was…*

S1: *yeah, I mean… gold had more mass!*

S2: *that's right, more mass, and therefore more density, and that's why it sunk more*

S3*: it could push more water, right! It had to do with the mass!*

S1: *Sure, it had to do with the mass… if the body had more mass, it could push… whatever was in front of it… faster!*

Int: *oh… let me see if I understand… You're trying to make an analogy with what happens when you put a body in water? Because water and air are alike?*

S2: *Well, yeah… I mean, we know water and air are not the same, but…*

S1: *like it's two identical bodies, but of different weight*

Int: *so, if bodies have different masses, different things happen?*

S1, S2, S3: *yes*

S3: *probably because one is more attracted by Earth.*

S2: *but… I mean… gravity is the same everywhere, but the weight of the body, the attraction on it towards the center of the Earth, that depends on its mass, of course*

Int: *ok, ok, so you remember that example that the teacher told you about and you're saying: "the force that air does on things must have the same characteristics as the force that water does on things", is that it?*

S2: (dubious, smiles) *they don't have the same characteristics… we're just… based on something that they explained to us, and which we know is right because it was a teacher who told us, we're trying to solve this problem because we're not completely sure that what we're thinking is right or not… we're just trying to back up the fact that…*

S1: *that it does have to do with mass, that mass does matter for the speed with which it reaches the ground.*

Making Sense of the Phenomenon is still dominating the frame. Recalling a classroom example, although enabled by the activation of Invoking Authority, is clearly a part of the overall sense-making. It allows students to seek coherence between a prediction, constructed on the basis of everyday experience, and trustable knowledge stemming from an authoritative source. This is a particularly interesting point: Invoking Authority is activated, but does not take over the frame, it is incorporated into the frame already established and productively adds to the sense-making activity already in process.

C. Analyzing acceleration: Invoking Authority takes over the frame

Upon addressing the following question (regarding the acceleration of the two balls) students show no hesitation in answering that they are equal. The interviewer asks them why they believe so, their answer shows that they have retrieved a piece of information from authority and that alone accounts for its reliability: "because its moving on Earth". This clear shift in framing triggers an intervention in the interviewer aimed at nudging them into their previous (productive) framing, and thus she asks if this is their answer considering the presence of air, or not, as this had been an important issue that they had been thoroughly discussing up to this point; they had even explicitly stated that their answers would change in vacuum or in air. S1´s utterances clearly indicate that their epistemic frame has abruptly been taken over by Invoking Authority: without even hearing the complete question from the interviewer an almost automatic answer is cited from authority, "on Earth, acceleration is 10 m/s^2". This answer is offered again, in the same manner, when the interviewer asks once again to clarify the question, emphasizing the unquestionable validity of the statement; that IS the value of acceleration on Earth. This answer is supported by a piece of information that has been recovered from an authoritative source, and is thus unquestionable. The frame is dominated by Invoking Authority, and making sense of the phenomenon is no longer activated.

S1: [Reading out loud] *then it says, the acceleration of the bowling ball is greater than / less than / equal to the acceleration of the soccer ball.*

S1, S2, S3: [immediately] *Equal!*

Int: *why do you think they are equal?*

S1, S3: *because it is on Earth.* / **S2:** [at the same time] *because it´s gravity.*

Int: *In vacuum? Or in air?*

(Pause)

S1: (seems puzzled by the question)

Int: *I´m asking this because you told me that if you considered air you would give one answer and that you would give a different answer in vacuum…*

S1: (interrupts) *on Earth, acceleration is 10 m/s2, or... well… -10 m/s2, depending on… the direction of the axis, the system that you choose, but here, on Earth, acceleration would be the same.*

Int: *considering the balls moving in air or in vacuum…*

S1: (still seems puzzled) *Pardon?*

Int: *considering vacuum or air?*

S1: *no! I mean, if here we have the bowling ball and the soccer ball, we drop them, acceleration is just the same! ... on Earth, gravity… acceleration, it´s just the same!*

There are several clues that indicate that the frame is dominated by Invoking Authority. Their first answer, given immediately and with great resolution, has the form of a "mantra" that is quoted unquestionably: on Earth, acceleration IS equal to that of gravity, and is the same for all bodies. The second clue is that, even when questioned by the intervewer ("I´m asking this because you told me that if you considered air you would give one answer and that you would give a different answer in vacuum") the students´ answer is once again to provide an unquestionable statement, quoting a piece of authority-supported information as sufficient warrant for its validity. They are no longer attempting to make sense of the interviewer´s question. This answer in no way attends to the issue regarding the presence or absence of air: they are providing an answer that is simply correct because it is thus sanctioned by an authoritative source. The third clue involves the uneasy, puzzled reaction of S1 to the interviewer´s question. This uneasiness is understood if we assume that, as making sense of the phenomenon is no longer activated, and the frame is dominated by Invoking Authority, S1 perceives the questioning about the presence of air as an unnecessary and uncalled for task. Finally, there is a strong indication of a frame shift in the tone of S1´s voice during this portion of his speech. There is a marked shift in demeanor in his voice. From a tentative, facilitating tone in their prior utterances, it goes to a sharp, directing one.

D. Negotiating frames

The following excerpt shows the effect of the interviewer´s epistemic "nudge" on S2, who activates Making Sense of the phenomenon once again and promotes a negotiation between two frames, one dominated by Invoking Authority and the other one dominated by Making Sense. This negotiation enables them to perform certain metacognitive activities. They are able to detect important issues about the problem itself and about their solving approach: a) they are solving a problem that is different from all the ones that have been part of their instruction in class; b) their answers on speed and acceleration are not consistent with each other (if accelerations are equal, and both balls are dropped from rest at the same height, their speed will be the same upon hitting the ground), c) what they know about the physics of falling bodies is not enough to account the fall of bodies in the presence of air.

S2: *but… I mean, we were so careful considering if there was air or not when they ask about speed, and now we´re not a bit bothered about that when they ask about acceleration, I mean, if there is air or vacuum. How come?*

S3: *because*, [in class] *acceleration is always the same.*

S2: *... according to what we´ve been doing, it´s always like, it's like there is no air... when that other teacher came that day* [a substitute] *remember she said "oh, ok, in all these problems you went like there is no air" and we said "well, no..." and she said "well, never mind, that´s ok, ´cause you don´t have to take air into account", because otherwise, everything changes. All the time we´ve been doing things* [in class] *like there´s no air!*

S1: *yeah… the thing is that we never… problems like this one… we never analyzed them in class, we never did problems like these.*

Int: *like this one, how?*

S1: *Like this, that we have to ask ourselves if things are falling in air or in vacuum...*

S2: *Sure we did! The thing is that we just pretended that there was no air… If we had to do this problem like we´ve been doing so far* [in class], *I´d say that the speed is the same for both, and that the acceleration is also the same...*

S3: *well, of course! I mean, if we say that the speed of one of them will be greater than the other one, and they start off with the same… from zero I mean…acceleration has to be greater for one than for the other! What I´m not sure now is what we said about their speeds, that one would be greater than the other… but, well yes, I think that´s ok! If the speed of the bowling ball, like we said, will be greater, then its acceleration has to be greater and it will take less time for it to hit the ground than for the soccer ball.*

S1: [back to a reflective tone] *the thing is that here it says "the acceleration of the soccer ball"... but when? Just as they start to fall? No… I mean, if we had to do this the way we do it in class, we´d have to say that the speeds are the same, that the accelerations are the same, and that it takes the same time for both...*

Int: *do you two agree with that?...*

S1: [interrupts, using an emphatic tone] *If we did it like we were in class, but... that´s not the way things really happen...*

S2: *Right!… if I drop this pencil case, full of pencils, and I drop it when it´s empty, the filled case will get to the ground first...*

In this excerpt, we can observe that, questioned by S2, S1 activates Making Sense once again. Moreover, upon realizing that their analysis, which have occurred within different framings (Making Sense, to reason about speeds, and Invoking Authority to answer about accelerations) are not coherent with each other, they engage in a frame-negotiating process. Both Making Sense and Invoking Authority remain activated (this last resource provides a "correct" piece of information, *i.e.* acceleration of gravity is equal to 10 m/s^2) Thus, they are enabled to detect and analyze the limits of a particular kinematic description that they have learned in class. One particular indication of this negotiation is S1´s doubt as to the moment the question on acceleration is referring to ("the acceleration of the soccer ball"... but when? Just as they start to fall?) In fact, another study performed on the basis of these data analyses the variety of explanations that these students provide on the phenomenon at this point, and shows how suitable their analysis is to address the problem of real bodies falling in air [27]. Their approach even includes the attempt to obtain experimental evidence on the matter by dropping similarly shaped objects of different weights and analyzing the validity of their observations.

In sum, this negotiation between frames is a fruitful epistemic move on their part, because it enables them to make the most of both epistemic stances. They take reliable information from authority, and feed it into their sense making activity. This not only lets them have a more accurate understanding of the phenomenon, but also starts them off in the activity of questioning the physical models that they accept in the classroom. The next excerpt shows the continuation of this process.

E. Establishing limits for instructional physical models

So far, the activation of Making Sense has enabled students to engage in a productive analysis: they are questioning the validity of the reasoning that led them to believe that the heavier ball hits the ground first and with a greater speed. They also understand that this is inconsistent with another result produced within the frame dominated by Invoking Authority: all bodies near the surface of the Earth fall with an acceleration of 10 m/s^2.

In the previous excerpt, we were able to see how students started of a frame-negotiation process. Thus, both Making Sense and Invoking Authority are activated. This new negotiated frame enables them to not only make a more accurate description of the physical phenomenon, but also to understand nuances of the physical models they have been using that had not been apparent to them up to now.

S1: *what I think is that… if there´s two bodies here, of the same volume, and different mass, the heavier one falls faster …I DON´T KNOW WHY THAT HAPPENS… acceleration is supposed to be the same for both, at first* *at least, but then, there must be something in the heavier body that that accelerates it more… I mean, acceleration is the same for both, its 10 m/s^2, but there´s got to be something that makes the heavier one go faster, something that we haven´t seen* [meaning something they haven´t been taught in class]

S3: *but if you say that happens, then at some point one must have a larger acceleration than the other...*

S1: *I don´t know… but there´s got to be something that makes the heavier one fall faster… and the only thing I can think of is that about having to push the air in front of it, and the heavier body can do that more easily than the lighter one.*

Making Sense is seen to be the resource that dominates the frame. It is the one that guides the cognitive task, and defines "what this task is about". However, the fact that Invoking Authority is activated, also leads him to accept, without question, that acceleration of falling bodies IS 10 m/s^2. The activation of both resources at the same time calls for a negotiation. Within this negotiation, S1 makes statements not only regarding the behavior of the physical system, but also regarding what they know and don´t know: heavier objects will fall faster + acceleration is that of gravity implies that "there´s got to be something that makes the heavier one go faster, something that we haven´t seen [in class]" This negotiation, which is a fruitful epistemic move, is once again evidenced when S1 imagines what he would do with a problem like this one (of a non-instructional type, that invited them to make physical sense) in a classroom situation (an environment presumably more akin to epistemic frames dominated by Invoking Authority):

S1: *If they gave us a problem like this in class, the first we´d have to do is say* [the bowling ball´s speed is] *greater,* [acceleration is] *greater,* [time is] *less… And ask the teacher: how do we deal with this thing about air?... because in our classroom problems we just solve them like... we never cared about friction with air... they never asked things like this "but different weight"... we did things without ever caring about weight.*

The negotiation between two originally different frames, characterized by two different resources (Making Sense and Invoking Authority) has allowed S1 to do more than just detect an inconsistency. He first realizes that the simplified kinematic model they know is limited, and too simplified to address problems such as the present one. From the beginning, these students addressed the problem as a "real one", in which the presence of air plays an important role, although this was not stated anywhere in the problem, and no problems such as these had been analyzed in class. S1 also has identified the locus of this limitation and is able to pose a clear question that he could make to his teacher in a hypothetical classroom situation. This negotiation, which involves the activation of "new" resources without deactivating the present ones, is what has been previously described as epistemic sophistication or epistemic flexibility [19, 20].

VII. DISCUSSION

The present case study shows the epistemic sophistication of these 5th year high-school students. This sophistication enables them to adopt a particular epistemic stance: any description they produce of the phenomenon must account for the fact, based on their experience, that, in the presence of air, heavier objects fall faster to the ground. In that first part of the interview, although their frame is dominated by making sense, Invoking Authority is activated to let them back up what they are thinking with what they have been taught. In the second moment of the interview, it can also be observed how this frame enables them to make a fruitful analogy (two crowns in a liquid) as a proxy to think about how the two different balls will fall in air. Invoking Authority, although not dominating the frame, allows the articulation of their reasoning with ideas that are worthy of trust due to the fact that they have been obtained from an authoritative source. They can, for example, reaffirm their hypothesis that "mass does have to do" with the speed, because this is consistent with the crowns-in-water analogy, which they "know is right because it was what the teacher said". A note worthy of mention is that these students had not been instructed in topics of dynamics, and the crown example had come up during a math lesson. They had only covered idealized kinematic models (constant accelerations, bodies falling in vacuum) in one dimension. This productive frame thus puts them in a powerful starting point to address contents of dynamics.

Students´ epistemic sophistication is also manifested in the way they negotiate two epistemic frames dominated by different resources. After a sudden shift to a frame dominated by Invoking Authority (Analyzing acceleration, third excerpt) a nudge from the interviewer through a question hints one of the students (S2) to propose a negotiation between frames, which is accepted by her peers. This negotiation continues until the end of the interview. The fourth excerpt (Negotiating frames) shows the usefulness of this negotiation, since students are able to detect inconsistencies in their reasoning and realize that their kinematic model has limitations. Furthermore, in the fifth excerpt (Establishing limits...), they are able to pinpoint those characteristics of the motion of falling bodies that they are unable to describe with the physical tools they have been taught (*if there´s two bodies here, of the same volume, and different mass, the heavier one falls faster …I DON´T KNOW WHY THAT HAPPENS… acceleration is supposed to be the same for both, at first at least, but then, there must be something in the heavier body that that accelerates it more… I mean, acceleration is the same for both, its 10 m/s^2, but there´s got to be something that makes the heavier one go faster, something that we haven´t seen*). Right after this, they are able to construct a query for their teacher in a hypothetical classroom situation. (¿how are we supposed to deal with this when there´s air?) Thus, this negotiation process has enabled them to benefit from the reasoning they are able to make in a sense-making frame, and at the same time to profit from the trustworthy source of information that is the teacher's voice. They have been able to obtain the "best from two worlds".

These students´ epistemic sophistication is comparable to a case already reported by Bing & Redish [20]. The interesting point in this comparison is that the subject in that case had already obtained a degree and had a considerable instructional history, as compared to the subjects in the present case, who are high-school students. These epistemic tools are an important part of the overall set of previous knowledge and abilities that these students have available for their future learning. In this sense, we believe it is important for instructors to be alerted of their existence, in order to be better prepared to detect them and to make a productive use of them during teaching.

ACKNOWLEDGEMENTS

This work was supported by Consejo Nacional de Investigaciones Científicas y Técnicas (Argentina) and by Agencia Nacional de Promoción Científica y Tecnológica (Argentina). Partial results were presented at the XI Simposio de Investigación en Educación en Ciencias, held in Esquel, Chubut, Argentina, October 24-26, 2012.

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