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Activation of a critical attitude in prospective teachers: From research investigations to guidelines for teacher education

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This paper is inspired by the widely accepted need to develop critical thinking in physics students and teachers. More specifically, it is focused on the development of a critical attitude in prospective physics teachers. The question of a possible interplay between the development of conceptual comprehension and that of a critical attitude prompted us to conduct a series of investigations with teachers at the end of their preparation. The goal of this paper is to provide a synthesis of five previously published papers on this topic in order to inform discussion about teacher preparation. Each investigation is centered on a particular aspect of physics, and all are based on in-depth interviews with different participants. We focus on prospective teachers' "intellectual dynamics," that is, the way their comprehension of nonobvious topics and their critical attitudes evolve during these interviews, taking into account metacognitive and affective aspects such as intellectual satisfaction and self-esteem. We characterize several types of intellectual dynamics: "early critique," "delayed critique," "unstable critique," and "expert anesthesia" and provide information on their frequency. An overall conclusion is that in this type of context, that is, a guided intellectual pathway of about an hour, the development of conceptual comprehension and critical attitude are most often deeply entangled. We discuss the implications of these results for future research and we advocate new objectives and strategies for physics teachers' preparation.

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I. INTRODUCTION

Most educators would agree that learning to think critically is an essential goal of education. As argued by Bailin and Siegel [1] (p. 188), "critical thinking is often regarded as a fundamental aim and an overriding ideal of education." Concerning science, Reddish and Hammer contend that [2], "More than helping students understand established ideas, science instruction must help them understand how those ideas, and further ideas we cannot now anticipate, come to be. Students must be prepared to contend with ambiguities, to make sound judgments about what to accept and what to question, to reconsider past assumptions and adapt to new discoveries. They must learn what a measurement means—and does not mean. They must learn how to evaluate their data and see the implications. In short, they must learn an adaptive expertise—the ability to respond effectively and productively to new situations and new knowledge as it develops." Still,

recently, the European Commission [3] reaffirmed that science education should "develop the competencies for problem solving and innovation, as well as analytical and critical thinking that are necessary to empower citizens to lead personally fulfilling, socially responsible and professionally-engaged lives."

All this confers a renewed importance to developing in physics students what is often termed "critical thinking." It follows that one prior objective for teacher formation is the development of critical thinking in student teachers themselves.

Note that the label critical thinking may refer to several components of critical ability, among which that of devising, conducting, and interpreting experiments to document a given question. Here we consider that students and teachers should also be able to critically analyze the extent to which a written explanation of the phenomenon under consideration is coherent and complete. More than twenty years ago, Millar [4] led a project in this perspective—Twenty First Century Science. One of the main arguments he put forward ([5], quoting Norris [6]), was that *Science (...) could not exist as an oral tradition; texts are essential, not optional. They are a constitutive feature of science—just as empirical data collection is. An understanding of science therefore requires the ability to read texts.* For instance, in France students at the secondary level are now expected to reflectively "extract information" from various

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resources available online or in popularization journals; thus at the grade 12 level, the preamble of the national program states the following: “Two skills occupy a central place at the senior level: “extracting” and “exploiting” information (Deux compétences occupent une place centrale en terminale: «extraire» et «exploiter» des informations)” [7]. More widely, in many countries, the “flipped classroom” [8] or other active learning teaching environments put the same request on students. The crucial role of critical thinking in physics is certainly not a new idea but it is worth examining to which extent and under which conditions prospective teachers manifest, or not, this faculty in a particular context: critical analysis of textual resources.

At this point, a crucial question arises: What links can be identified in physics students or student teachers between the development of critical attitude and conceptual understanding? This question recently incited us to conduct a few research investigations focused on the codevelopment of critical attitude and conceptual comprehension. These studies are based on in-depth interviews with prospective teachers on various topics of physics, thus allowing a fine-grained analysis of their conceptual and critique pathways. Rather than investigating possible correlations between conceptual understanding and particular skills, we centered on the very process by which conceptual understanding and critical attitude interfere during an interaction with an interviewer, in this case a physicist.

The goal of this paper is twofold. On the one hand, we intend to synthesize those of these studies that are already published under a detailed format: The topics were the hot air balloon [9], radiocarbon dating [10], how a survival blanket works [11], molecular interactions and osmosis [12], and capillary ascension [13]. Consistently with our research goal, each of these studies includes a detailed and, to a greater or lesser extent, novel content analysis; a specific method for conducting and processing the interviews; and detailed findings concerning the interplay between conceptual and critical development in advanced students. It seems to us that it is useful to present the convergent and complementary contributions of these studies in a relatively compact format.

On the other hand, based on these findings, we want to discuss the crucial question of teacher preparation by reviewing possible goals and strategies in this regard.

In the next section, we situate our research in relation to the existing research literature. In Sec. III we outline our research investigations and synthesize the findings. In Sec. IV we propose some guidelines for teacher preparation. We conclude with a general discussion of the contributions of our investigations and a research agenda.

II. RATIONALE AND RESEARCH QUESTIONS

In the context of this paper, what we mean by “critical attitude” or “critical faculty” does not refer to the whole range

of understandings encountered in the research literature on critical thinking. The meaning we ascribe here to these expressions relies on an epistemological position. We see physics as a science aiming at a coherent and parsimonious description of the world, a few laws accounting for a large set of phenomena in a specified range of validity [14,15]. In such a framework, critical faculty refers to the capacity to detect self-contradictory statements, statements that contradict basic laws of physics, and very incomplete explanations. Here, we envisage situations in which contestable statements can be identified based on a relatively simple argument, where the adjective “simple” refers to what may reasonably be expected of the concerned population.

In so doing, we leave aside a large part of what is defined as critical thinking by cognitive scientists, who utilize very wide definitions. For instance, in Willingham’s definition, critical thinking concerns “critical reasoning, decision making and problem solving” and is characterized by three key features—effectiveness, novelty, and self-direction [16] (p. 11). Abrami *et al.* [17] (p. 1002) state that critical thinking denotes “the ability to engage in purposeful, self-regulatory judgment.” Ennis’s [18] (p. 23) definition states that “critical thinking is the correct assessing of statements” whereas McPeck [19] (p. 7) chooses a more domain specific but still very large definition: “the appropriate use of reflective scepticism within the problem area under consideration” (see also Refs. [20–28]).

We also leave aside a large part of what is often looked into concerning students’ ability to criticize public accounts of science. Indeed, as has been argued by Jiménez-Aleixandre [29] (see also Ref. [30]), several aspects of critical analysis can be envisaged. Among these is the ability to criticize the sources of the texts under consideration with respect to possible asymmetric relationships of power. Although quite relevant, this critical analysis of the status of experts [31,32] is not included in our perspective, nor do we consider other abilities such as those listed by Jiménez-Aleixandre and Puig [33].

Among physics education researchers, critical thinking is universally deemed to be an essential component of the scientist’s activity. However, what is highlighted in this register is most often that student scientists should criticize their own lines of reasoning or those expressed during a discussion between peers, with a special focus on what can be concluded from experiments [2,34–36]. Here we consider the situation of an individual confronted by any textual or visual resource—a “Text” in what follows—designed by a person who presents herself as an expert whose explicit or implicit aim is to explain something. To our knowledge, the ability to critically respond to such a situation has not been much investigated in previous research [37] nor advocated in relation to teacher preparation, even if, concerning texts written by students, the questions posed by, and the benefits of, peer assessment and model critiquing are more frequently discussed [38–41].

In research literature on psychocognition, the question of the possible links between critical thinking and other elements of context is a long debated issue. As summed up by Tiruneh *et al.* [42]: “Whether CT (*Critical Thinking*) skills are general, domain-transcending set of skills that can be productively applied in any domain, or are specific to a particular domain, has been highly contentious. On the one hand, some scholars [43–45] claim the existence of a set of CT skills that are general and applicable across a wide variety of domains such as science, history, literature, psychology, and everyday life, on the ground that CT tasks across domains share significant commonalities. On the other hand, some other scholars [46–48] emphasize that the ability to think critically is largely associated with specific criteria within a domain.”

Here, based on in-depth analysis of long interviews, we attempt to inform the process by which a conceptual understanding and critical attitude interfere (or not) when a student teacher is confronted by contestable explanations. It is important to note that the goal of our investigations is to address this process rather than to evaluate a particular teaching environment. In particular, we do not claim to illuminate the much-debated question of which type of instructional intervention would result in better general critical thinking skills [17,42,49].

That said, we took Willingham’s position into account, “Critical thinking is not a set of skills that can be deployed at any time, in any context” [50] (p. 22); and one element of context that we attempted to investigate is the physics content at hand. More precisely, we considered it fruitful to analyze in detail how conceptual comprehension and critical attitude develop when students are confronted by various explanations of a nonobvious topic. We chose to conduct a series of investigations of this type, each devoted to a particular physics content. It seems likely that any convergence in results across different topics would lend stronger support to our conclusions than a single investigation—all the more so in light of the small samples. Similarly, any divergence between results across different topics would pose useful questions about the contextual dependence, validity, or complementarity of our results. As stated, the chosen topics were the hot air balloon [9], radiocarbon dating [10], how a survival blanket works [11], molecular interactions and osmosis [12], capillary ascension [13]. All were assumed to be at once nonobvious and partly accessible to the participants, an assumption that is compatible with our results. In choosing these topics, we aligned with Gunstone’s view of metacognition: “One aspect of content appropriate for the achievement of metacognitive purposes is that it is neither already understood nor totally unfamiliar” [51] (p. 145). Note that looking into the physics content as a relevant variable for our research question necessitates an in-depth content analysis and the critical evaluation of several levels of explanation for the same topic. The search of a possible

dependence of student teachers’ critical attitude on their comprehension of a topic incited us to try to intervene gradually on their conceptual mastery, adopting the format of concept driven interactive pathways [52]. We also injected in the discussion some original analogies, thought provoking situations, or modeling tools; this in order to observe whether these inputs enriched participants’ comprehension and/or their critical responses.

It is worth noting that the adoption of a critical attitude *vis-à-vis* an explanation requires some awareness of one’s own state of comprehension and some idea of what it is to learn science. These may be characterized as “metacognitive” features. In line with Vermunt’s position [53], we therefore see critical attitude as a component of metacognition—that is, as an essential condition for active self-regulation of one’s own learning processes.

Additionally, enacting a critical attitude is a means of expressing dissatisfaction—more positively, it evidences a search for intellectual satisfaction. This might be defined as “a feeling linked to the impression of having understood a complex topic to a certain extent, one that can be identified quite clearly, this being accomplished with a good quality/cost ratio” [9,54]. Note that we do not consider here a kind of motivation that would be necessary for students to engage with physics, but a feeling that should be a product of learning [55]. That being so, the present series of investigations also documents the extent to which the intellectual path proposed to interviewees fosters their “intellectual satisfaction.” We also take the view that posing questions that directly challenge an explanation implies an active search for meaning, depending in part on psychological factors such as self-esteem or “self-efficacy” [56]. As these metacognitive and affective components of students’ critical attitude seem *a priori* difficult to unravel, they are designated here by the compound label metacognitive critical affective (MCA). We examined how these MCA factors may evolve in conjunction with conceptual comprehension. In other words, our aim with these pieces of research was to characterize students’ “*intellectual dynamics*” during interaction with an interviewer.

Overall, we do not see the student teachers as “having” (or “not”) a critical faculty, but as individuals adapting the judgments they accept to express to various elements of context—elements that may evolve in time. We speak of a critical attitude as related to an observable activity, rather than of a feature that would characterize a given individual as such. Consistent with this position, we speak of persons who *activate*, or not, their *critical potential*, and our goal is to inform the conditions of such an activation. In particular, we coin *critical activator* a conceptual input, here on behalf of the interviewer, that turns out to be decisive to trigger a *critical attitude* in interviewees who were previously reluctant in this regard. Key ideas used in our rationale are summed up in Table I.

TABLE I. Some key ideas informing the research questions.

Conceptual comprehension (a level of)	A (level of) knowledge of concepts related to a given phenomenon or class of phenomena, including the meaning of related terms and links between concepts, all this being referred to a class of physical situations, and oriented by a search of a coherent and parsimonious description of the world.
Critical attitude or passivity	Attitude evidenced (or not) by participant' comments about inaccurate documents and/or self-critique of their own previous responses during their search for comprehension and coherence.
Critical potential	A (hypothetic) pre-existing ability to formulate critical comments.
Transition to critique	When a participant moves from passivity to a firm critical attitude.
Critical activators	Elements (here introduced by the interviewer) that trigger the participant's critical attitude.
Critical development	More frequent occurrence of a firm critical attitude in a given individual.
Intellectual dynamics	The interplay (here in the course of the interview) between critical attitude and the development of conceptual comprehension, including metacognition and affects (here metacognitive-critical-affective aspects or MCA) such as the search for intellectual satisfaction, pleasure or frustration in this regard, views on learning, self-esteem, doubt and self-critique.

III. SOME RESEARCH INVESTIGATIONS: CONVERGING AND COMPLEMENTARY FINDINGS

All of our previous investigations used in-depth interviews with advanced students, that is, mainly prospective teachers at the end of their preservice preparation [10–13] and, in one case [9], future journalists. In each case, the participants were presented with a series of documents and, for each one, the opening questions were as follows: *Do you consider this explanation appropriate and useful for yourself? For your students? If yes, which elements justify your positive judgment? If no, what would you add or change? Why?* The interviewer always gave the participant plenty of time to express him or herself on a text before providing new elements for reflection. The interviewees were clearly informed that the goal of the discussion was not to assess their understanding of the addressed topic, but to know their opinion of the explicative value of a text.

For brevity, we first illuminate two main types of intellectual dynamics based on the study about radiocarbon dating. We then outline to which extent the findings from other investigations confirm or not, and/or complement these preliminary conclusions. Some additional information concerning the content analyses is provided in Appendices A–D. This last appendix also briefly illustrates our coding procedures.

A. Radiocarbon dating: Two main types of intellectual dynamics

The topic of radiocarbon dating is well suited to our purposes, in that it seems well known, but its details are far from obvious, and many incomplete explanations can be found in popular accounts. In fact, beyond the exponential decay of radiocarbon in dead organisms and the role of ^{14}C half-life (5730 years), a *relatively* complete and coherent explanation of this process should at least include a series of conceptual nodes summed up in Appendix A. For instance, the reason why it would be reasonable to admit

that there is a steady value of the ratio of concentrations [$^{14}\text{C}/^{12}\text{C}$] in the atmosphere is by no means obvious.

For this investigation [10], we selected five documents from the Internet that provided incomplete explanations as compared to the list in Appendix A. We also designed a sixth document to explain how a steady state ^{14}C population can be reached and maintained in the atmosphere from an unbalanced initial situation. Ten prospective teachers were then presented with these documents in order of increasing completeness. For each document, the interviewees were invited to state to what extent they were satisfied, or whether they would need further information. We do not claim that students really appropriate each new explicative element provided by the successive texts. However, we can at least say that at each step, the discussion has a good chance of being enriched on a conceptual plane. Thus, when speaking of students' conceptual development in the following, we refer to a hypothetical aspect of their intellectual pathway.

Concerning radiocarbon dating, an example of a response considered to exhibit a critical attitude would be “How is it that there is a constant proportion of radiocarbon in the atmosphere? There is no radiocarbon decay in the atmosphere? They don't explain.”

Transcripts were processed at two levels of analysis: a conceptual level—not commented on here—and MCA aspects. Our MCA indicators included levels of agreement, types of questions posed (i.e., anecdotal, such as about how the detector works; or “crucial,” that is, concerning one of the arguments listed in Appendix A), and levels of intellectual satisfaction or frustration.

The findings indicated that most students needed to reach a threshold of comprehension *beyond mere logical necessity* before activating their critical potential. For instance, there is no need to know how radiocarbon dating works to ask, after the most incomplete text, why the concentration of ^{14}C atoms in the atmosphere would be constant in time, as if there was no radioactive decay in the atmosphere. However, it is observed that such a question

is not raised by students until a certain level of comprehension of the phenomenon is reached. Once this (student-dependent) threshold is reached, agreement (“It’s very complete.”), moderate satisfaction (“It gives an idea of the phenomenon, after that ...”), and anecdotal questions disappear, being replaced by frustration (“It poses a problem more than it solves ...”, crucial questions (“Is that a necessity? Had it to reach a state of equilibrium, or is it just by chance that rates of formation and decay coincide? I ‘m stuck!”), critiques and self-critiques (“It’s not an explanation”), and an active search for comprehension until the student is finally satisfied with the most complete explanation (“It gives an answer to all my questions”; “I think I had never gone so far”). We describe this dynamics of codevelopment as “*delayed critique*.”

For a minority of participants (2/10), we also observed a persistent absence of critique, regardless of the incompleteness of the explanation at hand. These students already knew the topic very well. They were happy with their own responses (“I’m very proud of myself”) and (therefore?) neglected to consider the texts for what they were—that is, deeply incomplete. These comments might be ascribed to a misunderstanding regarding what was asked in the interview, whereas the other participants’ responses (just cited) suggest they had properly captured the goal of the discussion. We suggest this misunderstanding is in itself a significant feature. Another nonexclusive hypothesis is that these acritical participants unconsciously completed what they were reading. We describe this syndrome as “*expert anesthesia of judgment*.”

To sum up, this investigation gives a first idea of how student teachers manage their intellectual resources when examining various texts interacting with an interviewer. Here, activation of interviewees’ critical potential according to their level of intellectual frustration and/or self-confidence was found to be linked to their comprehension of the topic. Two intellectual dynamics were identified: delayed critique and expert anesthesia, thus providing strong support for the thesis of a direct interplay between conceptual and critical aspects of student teachers’ development. Note that the first one—*delayed critique*—may seem an obvious finding, whereas the second—*expert anesthesia*—is more unexpected. With regard to delayed critique, it is tempting to invoke the hierarchy proposed by Bloom’s taxonomy [57], according to which evaluation is a higher-order process than understanding. This would explain that student teachers would not feel comfortable criticizing a text before seeing themselves as conceptually competent in the addressed topic. The phenomenon of expert anesthesia partly dissipates this impression of obviousness, at least underlining that conceptual comfort is not a sufficient condition for critique. Moreover, posterior investigations reveal that some individuals manage to overcome their feelings of incompetence and to produce relevant critiques even if they know little about the addressed topic.

B. Hot air balloon: The prevalence of delayed critique

In retrospect, a previous investigation [9] appears to confirm the prevalence of delayed critique in advanced students. The target of this study was to examine to which extent 14 future journalists share a concern for coherence when writing a popularization paper. The participants were interviewed about a (simulated) popularization paper about hot air balloons. As is currently done in physics textbooks or internet documents, this paper based the explanation of the working of a hot air balloon on the hypothesis of an isobaric situation: internal and external pressure would be equal to “atmospheric pressure” at the altitude of the balloon, implicitly a unique value. This hypothesis is inconsistent with the very basis of fluids statics, where sustentation is intrinsically linked to the existence of pressure gradients. Even without advanced knowledge of this topic, it is possible, in principle, to wonder how the envelope would be pushed upwards by a gas which exerts the same pressure on each side of each small part of it. Or else, the directional isotropy of the gaseous situation would suffice to call into question a vertical up thrust. In fact, it has been observed that despite a progressive awareness that this hypothesis was invalid, there was a large delay before the participants accepted to explicitly critique the paper under study. Nearly all (12/14) interviewees waited to have reached a first coherent explanation of the hot air balloon’s sustentation (Appendix B) before clearly stating—often with indignation—that the paper was contestable in terms of physical rationality.

These results give support, we suggest, to the prevalence of delayed critique in a population which, at the beginning of the discussion, does not feel in a situation of complete mastery of the topic under study, as was the case of these student journalists. With this sample, we did not observe any expert anesthesia, given their low mastery of the topic. But it is worth noting that the remarkable tolerance of textbook writers and physics teachers [55] with respect to the “isobaric hot air balloon” suggests a collective syndrome of expert anesthesia in professional physicists.

C. The survival blanket: Early critique despite low conceptual mastery

Another physics content was used to test the generalizability of the first findings. The topic was how to use a survival blanket to protect against hypothermia [11]. The participants ($N = 7$) had never been taught this topic before. In this case, instructions for use found on the internet or on the items on the market align with a common idea, that is, the highly reflective side of the blanket, “silver” side, should be put inside, in order to “reflect the heat” toward the body to be protected. This line of reasoning does not take into account the role—more or less emitting—of the external side. In current items, the blanket is made of a thin (13 μm) sheet of “Mylar” with a silver side highly reflective and therefore little emitting and

a gold one, less reflective and more emitting. These different radiative properties were made clear at the very beginning of the discussion, when participants were presented with a simple experiment unambiguously showing the relatively low emittance and high reflectance of the silver side as compared to the gold side [11] (p. 24). This state of affairs should raise a dilemma because maximizing the reflective effect inside the blanket entails to put outside a surface which favors outwards radiation (a content analysis is summarized in Appendix C). We sought to discern whether or not, and at what step in the interview, the participants would express their dissatisfaction with the current explanation and directions for use. Beyond a rich exploration of participants' lines of reasoning, not elaborated on here, the main finding of this investigation was a prevalence of the delayed critique (6/7). This effect might be reinforced here because, in this case more than in the previous ones, there is a common line of reasoning to be overcome, that is, a linear causal reasoning [58] that follows the path of heat from the body to the blanket then back to the body, and ignores the systemic approach needed here ("Bah it [*silver*] reflects much, it is one more reason to keep it near us given that it will reflect the energy that it will receive from us"). Another finding, although only symptomatic, is the case of an early critique which was observed with a participant. What makes her case emblematic is that her previous knowledge of radiant processes was very low, thus confirming that such an intellectual dynamic is possible. Despite this low conceptual mastery, she was able to take into account the elements of knowledge at her disposal to express her dissatisfaction, this without waiting for a complete solution of her dilemma: "I have a problem (with this explanation)!" In this case, what served as an activator of critique is the initial experiment that the interviewer helped them interpret in terms of relative emittance or reflectance of each side of the blanket.

D. Osmosis: The importance of meanings, even for mundane phrases

The topic of osmosis was exploited in the same vein [12]. On the conceptual plane, the important point is that an equilibrium between two solutions with the same solvent and solute separated by a semipermeable membrane is reached if and only if the chemical potential of the solvent in the presence of the solute is the same on each side of the membrane. Knowing that this chemical potential is a function of both pressure and solute concentration, this equality between chemical potentials means the pressure and solute concentration are either both equal or both different on each side of the membrane.

This complex topic was mastered by none of the participants ($N = 5$), although they had heard of it during their previous studies. No expert anesthesia was expected nor observed. For brevity, the focus here is on the critique raised, or not, by a type of document presented at the

beginning of the interview, on the one hand, and on an activator of critique that revealed particularly efficient concerning erroneous lines of reasoning about pressure in liquids, on the other hand.

Figure 1 recalls a typical situation of osmosis and Fig. 2 shows an account of the same phenomenon as proposed by Wikipedia or other online resources, as well as some textbooks. In these documents, it is suggested or explicitly stated that two solutions of different solute concentration, separated by a semipermeable membrane, will evolve due to the transfer of the solvent through the membrane from the less concentrated solution to the other one, until the concentration would be identical in the two compartments. According to this view, in a U tube under given external pressure, with the membrane at the lowest point, and starting with solutions of different concentration and same volume, the final situation would be the presence of a solution of the same concentration in the two legs, with one leg more filled than the other (Fig. 2). Incidentally, this means the pressure on each side of the membrane would differ, whereas the solute concentration would be the same; consequently, the chemical potential would not be the same in the two solutions. Such a situation is therefore impossible.

The participants were presented with the documents shown in Fig. 2 at the beginning of the interviews, only two expressed their doubts concerning the scientific validity of these. One interviewee argued that diagram (a) in Fig. 2 would mean that the content of the right leg might be in equilibrium with the same content on the left-hand side (same concentration and same volume) as well as with a different content (same concentration and larger volume), which seems very unlikely. The other participant had a no less valid argument: a thought experiment with, at the beginning, pure water one side and a solution with nonzero solute concentration on the other side. In such a case, he argued, pure water would pass endlessly toward the other compartment because the concentrations would never equalize. It is to be noted, however, that this second participant soon withdrew his critique, as if he had some doubts about the validity of his own argument. The other participants criticized these documents only much later in the interview.

In terms of confirmation, the study brings about the following elements, in this sample and for this topic:

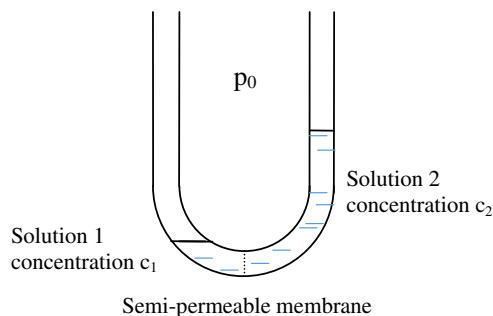
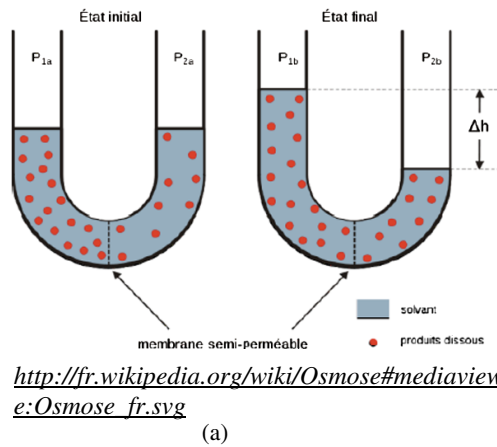
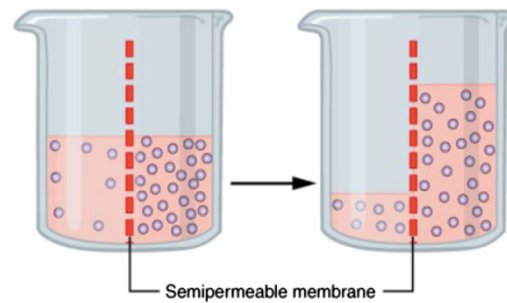


FIG. 1. A typical situation of osmotic equilibrium ($c_2 > c_1$).



(a)



(b)

(c) "At equilibrium, solute concentration is the same on both sides of the membrane.

FIG. 2. An idea often suggested (a),(b) or explicitly stated (c) ([59], p. 110).

prevalence of delayed critique, rare early critiques, including one which was not maintained over time.

In terms of activation of critique, a thought experiment injected by the interviewer revealed decisive. The physical situation is mundane—a glass of water is isothermally brought to the summit of Mt Blanc—but the questions are unusual: were pressure in water only a matter of kinetic pressure ($p = NkT/V$ in usual notations), then how is it that pressure in water is the same as in the air just above, despite a density much larger, and how is it that with the same temperature as at sea level, the pressure in water is half as big at this altitude? A discussion about these questions was expected to focus the interviewees' attention on the importance and variability of molecular interactions in liquids. It showed very efficient to illuminate the meaning of the phrase "pressure in water," and this conceptual progress triggered relevant critiques, self-critiques, and metacognitive comments in participants. Briefly put, what revealed an activator of critique here was an opportunity to better grasp the meaning, that is the conceptual content, of a phrase apparently mundane—pressure in water—but in fact heavily laden on the conceptual plane. Beyond confirming the relevance of the delayed critique (with the infrequent exception of early critique) to characterize participants' intellectual dynamics, this study spotlights that, in order to critically analyze an explanation, it is of decisive importance to master the meanings of some apparently usual phrases; even if this may be far from sufficient, as shown in particular in the investigations.

E. The case of capillary ascension: Unstable critiques

With the topic of capillary ascension, the analysis of participants' critical attitude was refined, taking the previous findings into account [13]. In particular, we were intrigued by two cases of an early critique with subsequent

withdrawal, one in the study about osmosis and one, pinpointed in retrospect, in the study about the survival blanket. For that reason, not only did we track the occurrence of several possible critical arguments in the transcripts, in order to put to the test the generality of the previous findings, we also attempted to evaluate, for each of these arguments, the stability of the participants' critical comments once articulated. To this end, we coded several possible responses to a given statement: clear acceptance (α), clear dissatisfaction (χ), and attenuated versions of each of these responses (μ). This allowed the tracking of what we defined as "withdrawals," that is, a change from a clear critique to an attenuated critique or toward a clear or mitigated acceptance, or else from a mitigated judgement to a clear acceptance.

Participants (prospective teachers, $N = 11$) were confronted by documents currently found in textbooks, as shown in Fig. 3.

Four possible critical arguments were identified in this regard.

C1—Diagram a in Fig. 3: Were the arrows intended to represent forces (by unit length of the contact line), and the diagram seen as a free-body diagram, this would not be balanced in the horizontal direction.

C2—Diagrams a and b in Fig. 3: Were the arrows intended to represent forces (by unit length of the contact line), these forces would be acting on a immaterial line, which does not allow use of Newton's second law.

C3—Diagrams a and b in Fig. 3: It is not possible to understand on this basis why the column of water remains above the level of water in the recipient.

C4—Diagram b in Fig. 3: The idea of a force vertically pulling the liquid upwards from above (glass-liquid attraction prominent) is incompatible with the fact that a vertical, plane, smooth glass wall can attract water only along the horizontal [61–63].

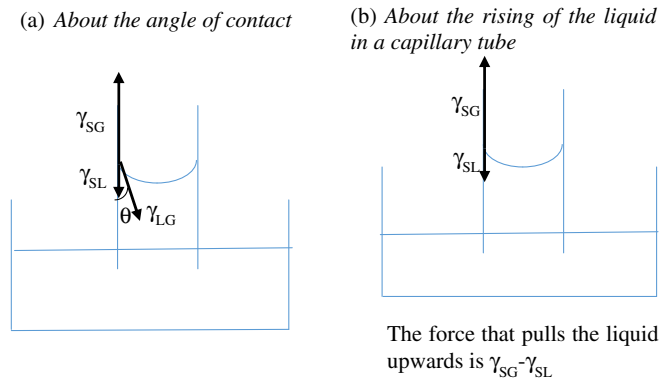


FIG. 3. (a) A current diagram introducing Young’s formula $\gamma_{LG} \cos \theta = \gamma_{SG} - \gamma_{SL}$, where γ_{LG} , γ_{SG} , and γ_{SL} are the coefficients of interfacial tension (forces by unit length), corresponding, respectively, to liquid/gas, solid/gas, and solid/liquid interfaces, and where θ is the angle of contact. (b) A diagram often used to account for the rising of a liquid column in a capillary tube, with a comment [60].

Consistent with our previous findings, the interviewer was careful to satisfy any query about the meaning of the phrases “tensile forces” or “surface tensions” in play, she discussed (on request) how these concepts link to a free energy approach.

Additionally, there were three other main inputs.

- (i) Concerning the attraction of water molecules by glass molecules, the interviewer pointed to the fact that, in the case of a wall of glass that was perfectly smooth and plane or cylindrical, the resultant attractive force would be horizontal for reasons of symmetry.
- (ii) Concerning C2 and C3, an analysis using dislocated diagrams (Appendix D), based on research in fluid statics [61,62], was presented to facilitate activation of these critiques while resolving the difficulty concerning the weight of the suspended column.
- (iii) Concerning C4, an analogy was proposed, based on the scenario of a centrifuge partly filled with liquid water [64,65]. In the case of stationary rotation, the profile of the free surface is a paraboloid of revolution (Fig. 4). A horizontal centrifugal force can be seen as analogous to attraction by the glass wall, piling up water molecules along this wall. As the level of water near the wall is higher than at rest, as is the center of mass of the liquid, a force larger than the weight of the water has necessarily been exerted on the water during the acceleration phase, and this force was exerted by the bottom of the recipient. In a stationary regime, the pressure at the bottom of the recipient is larger near the wall than near the axis of rotation.

This analogy is of course incomplete, especially in terms of the dimensional scale of the phenomenon of interest. Nevertheless, it draws attention to the need to consider the *whole* system in order to understand a situation that is at first sight paradoxical: a horizontal force that seemingly has a vertical effect.

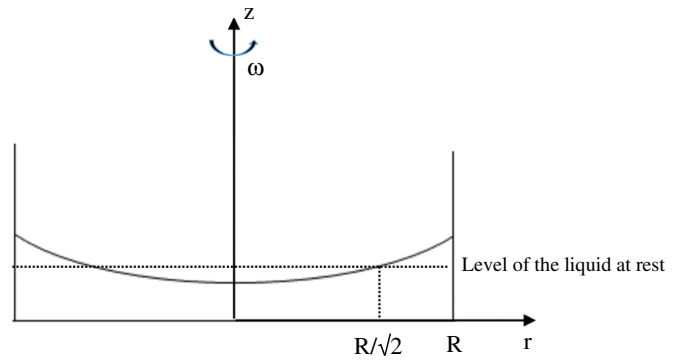


FIG. 4. Rotating centrifuge filled with liquid (angular velocity ω): level of liquid in the absence of a lid in the stationary regime [64,65].

The findings confirmed, here too, that the dominant dynamic was delayed critique, including its extreme version: persistent absence of critique. At the end of the interviews, only five participants in eleven had finally expressed (usually very late) a firm critique of the four arguments. Still more striking are the multiple attenuated formulations (μ), the index designating the concerned argument:

- (i) The vocabulary is not well chosen. (μ_4)
- (ii) Err, I still find this diagram a little confusing. (μ_2)
- (iii) Normally, there should not be a particular direction (*a vertical one*). (μ_4)
- (iv) It was not necessarily plausible (*a force pulling the liquid upwards*). (μ_4)
- (v) It suits me in that sense that there is no manifest error. (μ_2)
- (vi) It’s not detailed enough. (μ_4)

These attenuated critiques were an important component of the multiple *critical withdrawals* observed in most participants, and which we associate to the label of “*unstable critique*.” 10 out of the 11 interviewees fell into this category for at least one of the critical arguments C1–C4. Only one participant adhered firmly to all critical positions once expressed. As already noted, our findings indicate some variability across participants. However, we also observed that a given interviewee might register an early critique for a given critical argument and a long-delayed critique for another. We also observed some variability in the intellectual dynamics observed according to the critical argument, as shown in Appendix D. It is worth noting the case of a participant who was satisfied to reach a new comprehension of the phenomenon under study (here capillary ascension, thanks to a new modeling tool—dislocated diagram: see Fig. 7 in Appendix D) and then relied on this acquisition to stop caring about the other explanations at hand: “Since I have this (new) explanation, it’s OK!”. We use the phrase *anesthesia by substitution* to designate this case of critical passivity.

Finally, in terms of activation of critique, participants took the conceptual steps targeted by the interviewer’s inputs with apparent ease, but the outcomes of these conceptual steps in

terms of critical attitude were less straightforward. In particular, the idea of horizontal attraction of water molecules by the glass wall was easily understood if not spontaneously arrived at, but this does not mean that a firm critique of the phrase “the force that pulls the liquid upwards” was quickly expressed or persisted over time. More generally, being able to explain the phenomenon with some words of a (relatively) common register (e.g., “molecules piling up against the wall”, “increased pressure”) was not sufficient to prompt stable critiques of the diagrams shown in Fig. 3. In this regard, numerous withdrawals or attenuations followed these conceptual steps forward and subsequent critiques. In contrast, the dislocated diagrams (Fig. 7 in Appendix D) proved comparatively efficient in provoking both conceptual progress and firm critiques.

IV. RECAPITULATION AND DISCUSSION OF THE RESEARCH FINDINGS

In summary, keeping in mind that these studies concern future teachers (in one case future journalists) discussing with an interviewer about a topic which is neither totally unknown nor quite obvious to them, we suggest that the findings lend support to the following views.

When confronted by very incomplete or inconsistent explanations supposedly designed by experts, the majority of participants ($N = 37$ in all) first show a prolonged critical passivity, then, thanks to the conceptual inputs progressively injected by the interviewer—questions, remarks, more consistent and/or complete texts, analogies, thought experiments, modeling tool—they start to express critiques, self-critiques, frustration, and a rich panel of metacognitive comments accompanied in the end by expressions of intellectual satisfaction. It is tempting to consider that they needed to reach a threshold of comprehension, not the same for all, before activating their potential of critique. We call this intellectual dynamics a delayed critique. What makes this case nonobvious is that the threshold in question is, most of the time, beyond logical necessity. Indeed, a few cases of early critiques attest that, in such discussions, it was possible to object to the arguments under study with a very limited knowledge of the topic. For instance: “They say that the concentration

of radio-carbon is constant in time in the atmosphere? How is it? There is no radioactive decay in the atmosphere?” Or else: “In an osmotic equilibrium, the solute concentration should be the same in the two solutions? But then, what if we start with pure water on one side? There will never be pure water on the other side.”

That said, it happens that critiques, be they delayed or early, reveal subsequently unstable, many attenuated expressions tending to negate the validity of a first critical argument, if not to claim the opposite. We then speak of an unstable critique. It may also happen that participants knowing very well the topic under study—a very infrequent case in our samples—turn out to be totally passive in terms of critique. Very happy with their own response, they show tolerance toward the texts submitted to their judgment, or maybe they complete or correct these unconsciously. We coin this case expert anesthesia. In a register which might be close to the latter, we also observed a case when a participant was happy to have understood a phenomenon, thanks to a conceptual input by the interviewer, and argued of this acquisition—a new expertise—to leave any concern *vis-à-vis* the incriminated text, like with a kind of explanatory substitution:

Once you have introduced this story of pressure (against the wall), it’s OK.

In these two cases, we can think that the persons in question see themselves as assessed relative to their own power of explanation, rather than invited to evaluate the explicative value of some texts. Alternatively, they see the latter activity as useless once their objective of comprehension has been reached.

Table II summarizes these different types of intellectual dynamics and Table III recapitulates the topics, samples, features worth noting in the incriminated texts, and the observed frequencies of the various intellectual dynamics. For compactness, and because they both reflect difficulty in situating oneself in relation to a critical argument, the intellectual dynamics delayed critique and unstable early critique have been grouped together in this table (for more detail see the references quoted above [9–13]). These two intellectual dynamics represent, for 5/8 of the items listed in Table III (col. 1), the majority of the cases, if not almost unanimity.

TABLE II. Categories used to describe participants’ intellectual dynamics [13].

Delayed critique	When the participant offers no critique of a given text until they reach a certain threshold of conceptual comprehension (specific of the individual) beyond mere logical necessity.
Early critique	When the participant quickly exhibits a critical attitude despite incomplete comprehension of the phenomenon at hand.
Expert anesthesia	When a participant knows the given topic very well but offers no critical judgment of a related text, however incoherent or incomplete it may be.
Anesthesia by substitution	When a participant accesses a satisfying explanation during the discussion and relies on it to give up any critique of a related text, however incoherent or incomplete it may be.
Stability or instability of critique	Absence or presence in the participant’s discourse of withdrawal(s) of a critical comment previously expressed.

Therefore, prevalence of a prolonged reluctance to, and/or instability of, critique in participants can be seen as relatively robust findings. This assertion seems valid across the type of physical contexts we used, that is, not totally obvious nor completely unknown to the interviewees. That said, we can observe that a simpler context like an unbalanced free body diagram was more likely to raise objections in participants than, say, invalid explanations about osmotic equilibrium.

This finding is not very surprising if we admit that, in order to detect an inconsistency or incompleteness in a text, many participants need to reach a threshold of comprehension higher than what is necessary on a logical plane: When the addressed topic can be considered as relatively simple, we can expect that this threshold will be more easily reached.

In discussing these results, we should keep in mind that what was included in the category early critique is not necessarily a spontaneous response to a unique question like “Are you satisfied with this explanation?” We also

count as an early critique a fast critical response to a non-neutral question by the interviewer, e.g., “In what direction do you think a molecule of water would be attracted by an infinite vertical plane glass wall” when the participant very soon concludes that such a glass wall cannot pull the water upwards. In the same way, a delayed critique is a comment that was observed not only late in the interview, but after many inputs and prompts by the interviewer in an attempt to trigger a critique in the concerned interviewee. Given this coding choice, our findings support quite significantly the thesis of a globally strong passivity or reluctance to critique in our samples.

It was particularly striking to observe the great instability of many critical postures, be they early or not. In other terms, the transition toward critique was often less sharp than might be thought after the study concerning the radiocarbon dating. It is likely that some circumstances can, so to speak, block off a critical stance in participants even after first occurrence.

TABLE III. Occurrences of various intellectual dynamics according to the topic and possible critical argument [13].

Topic Incriminated aspect in the explanation	Sample	Features of interest in the documents	Early stable critique	Delayed and/or unstable critique	Expert anest. or anes. by substit.
“Isobaric” hot air balloon	14 student journalists	Hypothesis that is incompatible with theory of fluid statics	2	12	...
Radiocarbon dating: Constancy of $^{14}\text{C}/^{12}\text{C}$ ratio in the atmosphere	10 prospective teachers	Very incomplete explanations Nothing wrong	...	8	2
The survival blanket: “Put the silver side inside to protect against cold”	7 prospective teachers	Incomplete, nonsystemic, explanation, in line with a common line of reasoning, restricted validity of the conclusion	...	7	...
Osmosis: “Same solute concentration in each branch of the U-tube at osmotic equilibrium”	5 prospective teachers	Statement invalid if external pressure is the same for the two branches	1	4	...
Capillary ascension C1 ^a A force diagram with unbalanced forces	11 prospective teachers	Modeling tool incompatible with a Newtonian approach, teaching ritual	6	5	0
Capillary ascension C2 ^a Forces on an immaterial line	11 prospective teachers ^a	Incomplete and/or invalid explanation, teaching ritual	1	10	0
Capillary ascension C3 ^a Sustentation of the column unexplained	11 prospective teachers ^a	Misleading statement, suggesting an invalid argument given the symmetry conditions	5	5	1
Capillary ascension C4 ^a The glass wall cannot pull the water from above	11 prospective teachers ^a	Unbalanced free body diagram, teaching ritual	5	6	0

^aFor capillary ascension, critical arguments C1 to C4 have been discussed by the same eleven interviewees.

One major factor in this respect seems to be a feeling of incompetence, as shown by many metacognitive comments:

As I have no particular competence in this domain, I am obliged to trust what I am taught (*24 turns*). I have no clear cut position because I am not competent in this... err, I think I am not competent enough.

This factor can explain why participants need to reach a threshold of comprehension that is unnecessarily high, before allowing a clear critique.

This kind of self-blockage is probably reinforced when the incriminated texts conform to some teaching rituals. For instance, we observed a great instability of critiques about forces “acting on a line” (capillary ascension, argument C2).

- (i) I take it because I always did so, but I never called into question the fact that it was legitimate to apply, err, forces on an immaterial line.
- (ii) It’s not that it worries me or not; it’s that it was my only conception, and this time, it shakes up the conceptions, actually.

In contrast, in the case of radiocarbon dating, the absence of a teaching ritual standing in the way probably simplified the participants’ intellectual trajectories.

Finally, we observed, quite expectedly, that when critiquing a text comes down to renounce a previous idea (cf. the survival blanket or, to a lesser extent, the “iso-concentration” osmotic equilibrium), it is still more difficult to adopt a clear and stable critical position.

Turning now to the conceptual elements which best filled the role of “activator of critique,” given the complexity and the variety the topics used, it might be premature to propose broad conclusions. That said, it is worth noting that we had to refine the idea of a “threshold of comprehension” that should be reached by most of participants before activating their potential of critique. In all the investigations, participants all reached a level of comprehension which was satisfying for them, in a discussion that lasted between an hour and an hour and a half. A high level of intellectual satisfaction was expressed in the end jointly with critiques, self-critiques, and metacognitive comments. For instance, concerning capillary ascension:

- (i) I have been told a little about the formula of forces, but just as a formula, without any meaning. And now, today, it gave them meaning, and I was pleased with that because I had thought a lot about these questions of capillarity without finding any answer.
- (ii) I have the impression that, when we try to simplify we completely lose the meaning of what we want to explain.
- (iii) Before, I was a long way from asking myself questions about this phenomenon.
- (iv) You destabilized me for a good while, yes, yes; I wanted to do well. I wanted to remember my courses. I wanted to regurgitate (*what I knew*).
- (v) [*To be critical*] it’s difficult, it’s very difficult.

But it is striking that comprehending the phenomenon under study was not always sufficient to trigger such a critical awareness. In the case of capillarity, for instance, it was a new modelling tool—a dislocated diagram—that permitted participants to enter into an explicit critical analysis of the diagrams under study, that is, to realize that a free body diagram with forces seemingly acting on an immaterial line was meaningless.

- (i) Yes actually, yes, because it’s not relevant, because in fact they make free-body diagrams that have no meaning at all; it may be convenient, but it is totally meaningless, this kind of thing.
- (ii) It was interesting; there are many questions that I had posed to myself—for instance, about this course at university. Now, I realise that I should have posed these too (*6 turns*). There are tools that help us to understand but are not sufficient.

This probably occurred because of the completeness and self-consistence of the conceptual tool introduced: concerning these diagrams, that is documents situated at the level of formal modeling, a mere description of the phenomena in terms of molecules piled up against the glass wall had been insufficient for the participants to call these into question.

Finally, cases of expert anesthesia or anesthesia by substitution suggest that the impression of knowing, be it in a superficial register, may block the activation of interviewees’ potential for critique. This intriguing case opens the door to further research, because for the time being we are reduced to mere speculation regarding the factors at play in these phenomena. In particular, this can hardly be referred to what Renkl *et al.* call “inert knowledge” [66] or with transfer difficulties that have been observed in the context of problem solving, precisely because what is at stake here is not problem solving but the critical analysis of explanations constructed by others. One of the possible causes for this link between comprehension of a topic and critical passivity towards a text addressing this topic is that the concerned person might unconsciously complete or transform this text. Another nonexclusive is that the intellectual value of critique is depreciated with respect to the production of a “right” answer. Still conjecturally, a focus on this concern—to exhibit proper knowledge of a topic—might even induce a participant to misunderstand the goal of the interview and the questions they are asked. Informing the validity of such hypotheses would be of interest particularly regarding their implications for teacher preparation.

V. FROM RESEARCH TO SUGGESTIONS FOR TEACHER PREPARATION

In commenting on these findings, we posit that it will be essential for teachers, in their future professional activity, to be able to detect whether or not they understand and/or are satisfied with an explanation found online or elsewhere. As stated, this need is not restricted to teachers, which ideally

should foster the same ability in their students. Teachers, students, and ordinary citizens will be, more and more, in a situation of “extracting information” from various sources and, in doing so, they will have to rely on their own conceptual and critical intellectual resources. We therefore think it crucial to search what can be done to facilitate the development of this component of teacher competence. This paper is our attempt at contributing to this major task. We are aware of the vast literature devoted to all that a physics teacher should know [67–77], what “tasks” they should be able to perform [78–80], what “habits” they should develop [81–84], but, to our knowledge, not much yet has been published concerning the specific ability in question here: efficiently using one’s own intellectual resources to conduct a critical analysis of a text, here related to physics.

A. Objectives for teachers’ formation

Our studies strongly support the thesis that critical attitude and conceptual understanding do not develop independently. In that sense, it would be risky to exclusively focus teaching on a given competence, for instance, critical thinking. Teachers should be aware of this strong interplay between critical and conceptual development. That said, it is not enough to advocate a thorough conceptual formation for teacher, or more widely a robust physicist practice, arguing that this will also free and support their critical thinking. We need to define more specific objectives for teacher formation to critical analysis.

A first important formation goal is to help teachers maximize what they can do, in terms of critique, when their knowledge of a given topic is weak or medium, which is very common in persons who consult resources, e.g., online. It is important in this regard to understand the value *per se* of detecting a contestable point in an explanatory text, this even without having yet in mind a satisfying explanation. This means developing in student teachers a feeling that they “have the right” to understand whether or not they understand, to be informed in case there is a missing link in a line of reasoning (and where it is), to react in case of internal inconsistency. In this perspective, relying on mere logic and on what one knows without waiting to know everything about the topic at hand is a highly valuable intellectual activity that deserves explicit formation. In other terms, we think it necessary to educate teachers to adopt the intellectual dynamics of early critique.

A first condition for this is a great attention to the meaning of the terms used in a text under consideration. A teacher educator can have important surprises on this point, as when the meaning of “pressure in water” turns out to be mysterious for their student teachers. But, for the rest, the conceptual requisites for effective criticism can be relatively low, as shown in the examples presented: convincing future teachers of this fact is an important

objective for their formation. Their feeling of incompetence is often a useful motive to work further on an ill-mastered topic, but it should not paralyze their critical judgment.

An important obstacle to critique is the existence of students’ previous ideas, in case the conclusion or the lines of reasoning of an explanation coincide with these. Expectedly, critiquing the text then becomes very difficult.

Another important risk is the existence of teaching rituals, i.e., those teaching strategies and explanations that are both in current use and never called into question, the prototype of which is the “isobaric” hot air balloon. It is extremely difficult for a future teacher to call into question such a ritual. For instance, a free body diagram with forces all “acting on a contact point” (or an immaterial line of contact) will be commonly accepted because it looks like a free body diagram with forces all “acting on” a center of mass. In both cases the forces are seemingly acting on a point (a dimensionless element). It is therefore important that future teachers keep their intellectual freedom with respect to such situations. Then, they will be open to the possible difficulties of their students, and their own questions will help them go further in their comprehension. For instance, they will realize that some points (centers of mass) are laden with mass whereas others (contact points) are not.

In summary, helping student teachers enact early critiques demands to keep in mind at least the following components of formation: help teachers realize the value *per se* of constructing a critical analysis of a given explanation, incite them to ensure that they understand the meaning of the terms or phrases used, help them activate their potential of critique even without mastering the “right” explanation, even if the proposed explanation is in line with a previous idea and even if it constitutes a teaching ritual. The importance of some of these components of formation has long been emphasized in the research literature [67–84], we propose here to involve them all in an explicit and coherent effort.

To facilitate the attainment of these objectives, it is probably necessary to help teachers to reconsider critically both the idea of a model and that of simplicity by distancing themselves from the idea that modeling a situation is essentially simplifying its description. A risk with this idea is that it seems to legitimate a prevalence of simplicity in the construction of models: if models were there to simplify our descriptions of physical situations, then it would be inconsistent to criticize the simplifications they entail. In such a perspective, an isobaric hot air balloon is an acceptable hypothesis because, as often heard during discussions about this topic, “It’s a model!” Alternatively, the difficulty in criticizing the schematic model currently used for capillary rise could indicate that, for the participants concerned, a model would be somehow immune to criticism by its very status. Therefore, it would be a valuable objective to make future teachers aware that models are not exempt from internal coherence and

compatibility with accepted laws of physics. Comments from some participants at the end of the interviews significantly illustrate this need: “By oversimplifying, we completely lose the meaning of things” or “They make free-body diagrams that have no meaning at all; it may be convenient, but it is totally meaningless, this kind of thing.” Such comments suggest that reconsidering the link between modeling and simplifying is a realistic objective worth considering for teacher preparation.

It may be more surprising that another goal of formation must also be considered, this time regarding student teachers who have a very good comprehension of physics. This concerns in fact any individual who has reached a thorough comprehension of a given content. Then, given the phenomena of expert anesthesia (among participants who are familiar with the addressed content when starting an interview) and anesthesia by substitution (among participants who are satisfied with an explanation during an interview), these persons should be helped to realize that they are in danger of critical passivity when they feel intellectually comfortable. This would help them understand that they might ignore the difficulties of their future students with an erroneous, misleading, or enigmatic text, due to their own tolerance.

In any case, it is useful to remember that the risk of critical passivity is even greater when the conclusion of a contestable text is in accordance with accepted physics, as is the case for the isobaric hot air balloon.

B. Teacher formation to critique: some strategies worth considering

One may wonder what specific environments would be productive to reach the objectives already articulated. There seems to be a consensus on a long list of what teachers should know and know how to do, particularly in the classroom. For instance, a great attention to the meanings of the terms employed in an explanation seems to be an obvious need [77]. However, our findings pose the question of a more complete and productive set of actions to be taken in teacher formation.

What was new to the participants in our studies, according to their final comments, is the type of experience they had with the interviews. As shown, they often articulated their surprise, their final satisfaction, and a retrospective critique of their previous education. Therefore, it would probably be fruitful to integrate in teacher formation more situations centered exclusively on critical analysis, leaving provisionally aside the concern to solve a problem or to find a correct explanation. In order to facilitate students' education to critical analysis, it is useful to teach them the most current objections that can be made to a text (e.g., internal or external inconsistency, logical incompleteness, linear causal reasoning) and some common pitfalls that can favor critical passivity (e.g.,

expert anesthesia, focus on exactness of the conclusion) or else some tests to verify that a conclusion is acceptable (e.g., extreme cases).

It is worth noting that the benefits of this type of intellectual activity is not limited to highly contestable texts. Any solved exercise can be proposed to student teachers asking them to work with the text as it is, check its internal consistency, extract and possibly extend its meaning, for instance, by modifying just one hypothesis and see what should be changed (see examples in Ref. [60], Chap. 5). In the quest for an explanation of a given phenomenon, using more or less complete and/or satisfying texts and asking for a comparative critical analysis would situate the future teachers in the realistic environment of a personal search for understanding. In such cases, the participants are placed in a situation of “critical availability,” that is, their role is explicitly to evaluate various arguments articulated by others, not directly to work out a problem. In the limited context of our investigations, this opportunity freed in the end the participants' judgments. The delays, to and fro and reluctances observed along the way are good reasons to practice this exercise more often. Additionally, one may expect a much higher quality of comprehension of the phenomenon under consideration after this phase of critical analysis. In this perspective, to criticize is a means of better understanding as much as understanding facilitates critique.

In terms of topics, a set of examples like those used in our investigations, or much simpler ones, may facilitate the work of teacher educators.

VI. CONCLUDING REMARKS

The investigations summed up have made it possible to characterize intellectual dynamics in student teachers confronted by contestable explanatory texts. The robustness of these findings across contents has been put to the test. Hypothetical psychocognitive mechanisms have been suggested to account for these phenomena. Consistently, some objectives have been advocated for teacher formation and some strategies are suggested, among others already advised for in research literature [80,84]. Multiple and complex aspects now remain to be explored.

First, it is worth noting that approaching the physics content with a double angle of attack, conceptual and critique, was a powerful incitement to conduct a thorough and partly novel content analysis of each topic. In this perspective, to comprehend is not only a condition for critique, it *is* understanding *and* critiquing. A topic can be considered as mastered by an individual or a group when appropriate explanations can be produced, their conditions of validity analyzed, their informative value possibly extended; *and* when contestable arguments can be appropriately discussed and possibly rejected. It goes with a

thorough concern for rationality and a considerable intellectual exigency. It often makes it possible to become aware that we thought we understood a topic when this was not the case. Additionally, it offers safer grounds when interpreting what is often called students' "naïve ideas." For these reasons, we consider it essential to make more explicit this critical dimension in teacher formation. At least can we say that the persistence of teaching rituals in physics teaching communities draws attention to this need.

That said, an important effort is needed to precisely evaluate what can be done in this domain and with which effects in the long term. Many obstacles stand in the way of student teachers' critical development, according to their own comments: "Why change a pseudo explanation if it leads to the correct result?"; "Why discuss a contestable argument if we are used to it since decades?"; "Why throw some doubt on an explanation if it will "mix them up" (the students)"; "It's difficult, it's difficult"; "Who am I to criticize what important people have written?" As is manifest in these comments, attempts at instilling the taste for early critique in future teachers puts into play psychocognitive aspects of decisive importance. For that reason, conducting research in this field cannot be expected to be simple. We tend to think that, in teacher formation, it is essential to consider jointly conceptual aspects and metacognitive-critical-affective aspects. But how to manage both lines of action as teacher educators and how to evaluate the impact of a given instructional environment remains an open and complex research agenda, to be conducted, we suggest, by focusing on intellectual processes and accepting their complexity, in line with Hammer and Sikorski's viewpoint [85].

APPENDIX A: RADIOCARBON DATING [10]

The conceptual elements needed to understand the process of radiocarbon dating are the following:

- (1) the need to know the initial proportion of radiocarbon to ordinary carbon in an organism at the time of its death;
- (2) the uniformity of this quantity in the atmosphere and living beings;
- (3) the constancy in time of this quantity;
- (4) the process of formation of radiocarbon;
- (5) the process of radioactive decay of radiocarbon;
- (6) how the balance between the corresponding numbers per second of radiocarbon atoms involved in these two processes results in a steady value of [$^{14}\text{C}/^{12}\text{C}$] in the atmosphere;
- (7) the constancy of the total number of nuclei (radio carbon + nitrogen);
- (8) the multiplicative effect of the existing numbers of radiocarbon and nitrogen nuclei in the destruction and creation of ^{14}C nuclei, respectively;

- (9) how this multiplicative structure explains the stable proportion of radiocarbon to ordinary carbon in the atmosphere.

APPENDIX B: THE SUSTENTATION OF A HOT AIR BALLOON [9]

A standard explanation of a stationary sustentation relies on Archimedes' principle: the up thrust due to the outside air on the whole ensemble (of volume V) is balanced by the weight of the volume V of the external air. The weights in question, corresponding to the same volume, are differentiated by different values for the density of air ρ , itself related to mean molar mass M , pressure p and absolute temperature T by the barely transformed ideal gas law: $\rho = Mp/RT$ where R is the constant of ideal gas. For a balloon of total mass m_c (for the solid parts), from Archimedes' principle, the Newtonian equilibrium is written

$$m_c + \frac{M p_{\text{int}}}{R T_{\text{int}}} V = \frac{M p_{\text{ext}}}{R T_{\text{ext}}} V,$$

i.e., assuming that the (mean) internal and external pressures are very close to their value p_0 at the opening, $1/T_{\text{Text}} - 1/T_{\text{int}} = m_c R/p_0 M V$.

Another approach, here using a cylindrical balloon for simplicity, of height Δh , makes direct use of pressure gradients: To first order we have at the upper level $p_{\text{ext}} \approx p_0 - \rho_{\text{ext}} g \Delta h$ and $p_{\text{int}} \approx p_0 - \rho_{\text{int}} g \Delta h$. The supporting force which acts on the upper horizontal face of area S balances the weight of the solid parts if, and only if, $m_c g = (p_{\text{int}} - p_{\text{ext}}) S$, which leads to the same expression as that produced by the standard treatment, $1/T_{\text{Text}} - 1/T_{\text{int}} = m_c R/p_0 M V$. The main elements of these two approaches are sketched in Fig. 5.

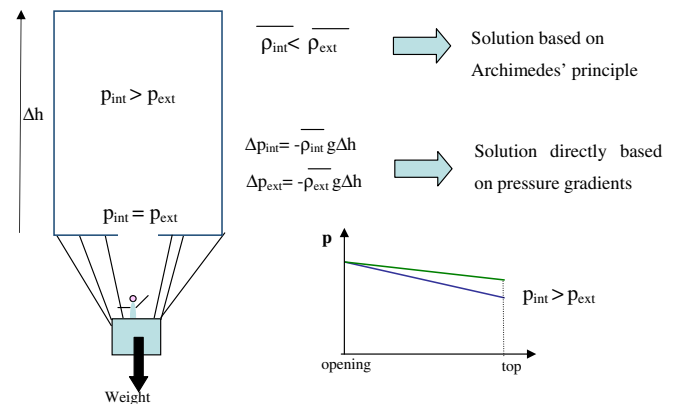


FIG. 5. Main elements of two explanations for the sustentation of a hot air balloon.

APPENDIX C: A LINEAR MODEL TO DECIDE WHICH SIDE TO PUT A SURVIVAL BLANKET TO PROTECT AGAINST COLD [11]

In a simplified structural model, three subsystems are considered, each isothermal at different temperatures: the body (T_b), the blanket (T_s), and the external air (T_e). Two successive subsystems exchange energy with net fluxes orientated from body to external air. It might first be remarked that impeding radiant transfer between blanket and external air by placing silver (low emissivity) outside would serve to maintain a higher temperature difference between these two subsystems. Impeding radiant transfer between body and blanket by placing silver (high reflexive power) inside would also serve to maintain a higher temperature difference between this second pair of subsystems. This seems to lead to a dilemma, as we cannot place the silver side both inside and outside.

In more detail, two successive subsystems exchange energy by two processes that intervene in parallel in each transfer zone: radiant(A)transfer and conductive-convective (C) transfer. In each case, net fluxes flow from the body to the external air. Each of these (four) fluxes are increasing functions of difference in temperature, with a coefficient of either conduction-convection (C)—linked to clothes, shape factor and meteorological conditions (unaffected by the orientation of the blanket)—or radiant, linked to the emissivity of the side turned towards the transfer zone and to shape factor.

Drawing on Vollmer [86], and taking into account the weak relative value of temperature differences considered here, a linear mathematical model can be used despite the nonlinear form of Stefan's law (for more detail see Ref. [87]).

Let C' , C be the coefficients of net thermal transfer via conduction and convection (C), respectively upstream and downstream the blanket; and let A' , A be the coefficients of net radiant transfer respectively upstream and downstream the blanket (for each side of the blanket concerned, silver or gold, A_s , A_g respectively). All these coefficients depend in particular on shape factors.

In stationary state, the total flux writes

$$\Phi = (C' + A')(T_o - T_b) = (C + A)(T_b - T_e), \quad (1)$$

which means, according to the orientation of the blanket, for silver outside

$$\Phi = (C' + A'_g)(T_o - T_b_s) \quad (2)$$

and

$$\Phi = (C + A_s)(T_b_s - T_e), \quad (3)$$

for gold outside

$$\Phi = (C' + A'_s)(T_o - T_b_g) \quad (4)$$

and

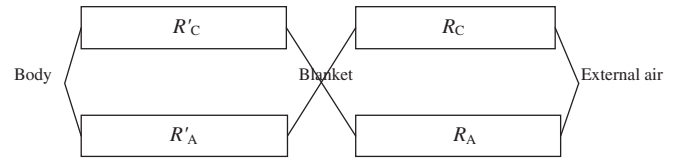


FIG. 6. Representation of the system between body and external air: R'_C and R_C represent resistances to energy transfer by conduction or convection; R'_A and R_A represent resistances to radiant energy transfer. These resistances are the inverses of the coefficients in use.

$$\Phi = (C + A_g)(T_b_g - T_e). \quad (5)$$

Formally, this model is equivalent to that of two conductive dipoles in series (Fig. 6), one between body and blanket and another between blanket and external air. Each of these dipoles is a set of two conductive dipoles in parallel (two modes of transfer).

This model leads to the conclusion that the low emissivity (silver) side should face towards the transfer zone having the lowest C coefficient of transfer. In case of dry weather (low C coefficient), the silver side (low emissivity) should face outward; for windy and wet conditions, silver should face inward. An easy way to remember this conclusion is that placing the smallest radiant resistance in parallel with the greatest conductive resistance would short-circuit both of the greatest resistances, so lowering the total resistance.

We have found no complete explanation of this process anywhere. Instead, online sources or instructions for use currently suggest that where there is a risk of hypothermia, silver should face inward, but no mention is made of the crucial role of meteorological conditions.

APPENDIX D: INTERVIEWS ABOUT CAPILLARY ASCENSION: CODING PROCEDURE AND TWO CONTRASTING EXAMPLES [13]

In order to map interviewees' intellectual pathways, we used codes denoting acceptance (α), critique (χ) or mitigated judgements (μ) with the corresponding exchange turns. The participants' questions on the meaning of coefficients γ (surface tensions) are also pinpointed (code γ). The interviewer's inputs and the targeted conceptual steps forwards (codes in Table IV, col. 2 and 3) are also mentioned. As regards dislocated diagram (code *DDIA*), it is important to note its main characteristic, that is, forces act on well-specified material objects (and not on an immaterial line), which allows a significant use of Newton's laws.

Concerning the MCA codes used here, $m+$, $!$, and $meta$ designate, respectively, intellectual satisfaction, surprise, and metacognitive comment.

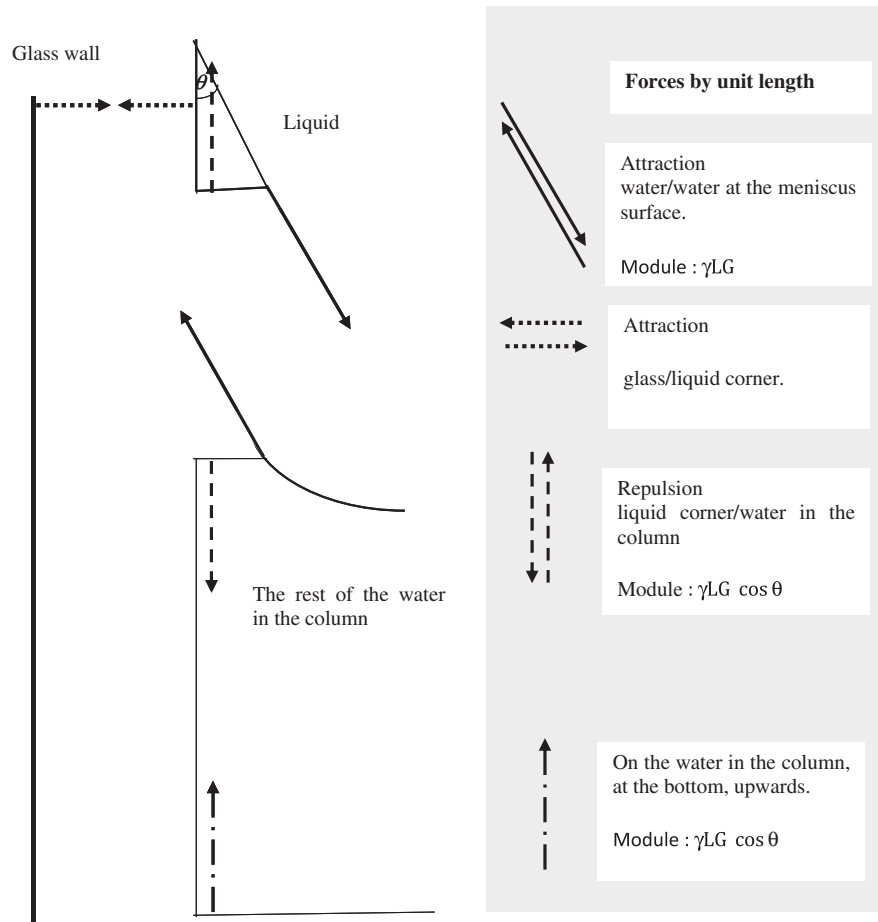


FIG. 7. *Dislocated diagram* of capillary ascension, in which several objects, defined by a unit length of the contact line and actually in contact, are represented separately (see text). The only complete free-body diagram (by unit length of the line of contact) is on the liquid corner. The weight of the liquid corner is negligible with respect to the other forces, and the weight of the liquid column, P is not represented (for a column of height h , $P = \rho_{\text{eau}} \pi r_{\text{tube}}^2 h g = \gamma LG \cos \theta \cdot 2\pi r_{\text{tube}}$). The role of gas pressure (here, atmospheric pressure) is not represented; it generates a normal force exerted on each external surface (even immersed) of the various objects in play (liquid corner, liquid column, glass wall, ...) whose total contribution to the Newtonian balances is zero as with any object located in a gas environment at a (locally) constant pressure [61,62].

In the tables used to map interviewees’ intellectual pathways, the chronological order of events can be traced both in terms of the numbers of exchanges and by means of left to right and top-down readings. The “life” of a participant’s view in relation to each critical argument

(C1 to C4) can be traced in the corresponding column, top down. In relation to conceptual steps forward, one can observe how they follow (or fail to follow) the interviewer’s inputs targeting each of them. Two examples follow (Tables V and VI).

TABLE IV. Codes for the interviewer’s main inputs and targeted conceptual steps forward in interviewees.

Interviewer’s inputs: brief description	Code for interviewer’s inputs	Targeted steps forwards
A question about the (in fact, horizontal) attraction of the water molecules by the glass, pinpointing the plane or cylindrical symmetry of the glass wall.	<i>HORI</i>	hori : Molecules attracted horizontally by the vertical wall.
A question or suggestion about a possible analogous situation (the centrifuge) in which the water’s free surface would be curved like the meniscus in Fig. 4.	<i>ANA</i>	ana : Molecules piled up against the vertical wall. push : An upward force is exerted on the fluid from below.
Modeling based on a dislocated diagram as shown in Fig. 7.	<i>DDIA</i>	ddia : Diagram understood and accepted: forces exerted on well specified material systems.

TABLE V. Mapping A 's intellectual pathway. In the case of A , we observe the precocity and multiplicity of questions about meanings, driving early and irreversible critiques of $C2$ and $C3$ (and implicitly $C1$, which was not considered because the diagram was "meaningless") while a question posed by the interviewer and subsequent step forward (hori) led her to a firm and irreversible $C4$ critique. The other inputs completed her reasons to be satisfied in the end, with retrospective critique of the previous teaching.

Int.'s main inputs	Quest.	Steps forward	MCA comments	C			
				C1	C2	C3	C4
	γ_{148}			...	χ_{256}	χ_{288}	
	γ_{314}				χ_{346}		
$HORI_{354}$		hori ₃₅₉					χ_{359}
	γ_{372}		meta ₃₈₀				
	γ_{390}						
ANA_{397}		ana ₄₀₆	m^+ ₄₁₂				
		push ₄₃₀	m^+ ₄₃₀				
$DDIA_{463}$		ddia ₄₆₆	m^+ ₄₆₆				
			meta ₅₄₈				
			meta ₅₈₈				

TABLE VI. Mapping F 's intellectual pathway. In the case of F , there are fewer direct questions about meanings, with multiple attenuated critiques and to-and-fro in relation to $C2$ and $C4$, although he was at ease with comprehension of the situation itself (hori, push, ana). There is great satisfaction at the end, particularly in relation to the dislocated diagram, even though the final formulation of his critique concerning $C2$ remains mitigated (μ).

Int.'s main inputs	Quest.	Steps forward	MCA comments	C			
				C1	C2	C3	C4
					μ_{96}		
					μ_{168}		
					μ_{199}		
					χ_{204}		
					μ_{212}		μ_{268}
	γ_{222}	hori ₂₆₈					α_{284}
		push ₂₈₂				χ_{288}	
				χ_{308}	χ_{372}		
$DDIA_{347}$		ddia ₃₆₈	m^+ ₃₆₈				χ_{420}
ANA_{377}		ana ₄₀₄			μ_{428}		
			meta ₅₀₆				
			m^+ ₅₀₆				
			meta ₅₁₂				

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