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ARTICLE

Abduction as a Mode of Inference in Science Education

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Abstract
The central argument of this article is that abduction as a "mode of inference" is a key element in the nature of scientists' science and should consequently be introduced in school science. Abduction generally understood as generation and selection of hypotheses permits to articulate the classical scientific contexts of discovery and justification and provides educational insights into scientific methodology, this being a particularly important issue in science teaching. However, abductive reasoning has been marginally treated in the philosophy of science until relatively recently; accordingly, we deem it important to perform an "archaeology" of the concept that considers C. S. Peirce's seminal contributions. We also choose to review contemporary treatments in order to recognise useful classifications to support more meaningful ways of teaching science and the nature of science. An elucidation of the participation of abductive inferences in knowledge construction seems necessary for us to derive conceptual input for the understanding and design of explanations in school science. Some prospective examples of "school scientific abduction" are discussed in the article through the lens of the results of our theoretical analysis.

1 Introduction

The aim of this article is to examine a possible role for abduction as a "mode of inference" in the construction of school scientific explanations. Explanation is here assumed to be the key epistemic goal of school science, a process directed towards obtaining "increased understanding" of natural phenomena based on scientifically accepted evidence (Osborne & Patterson, 2011) and especially through the use of scientific *models* (Adúriz-Bravo, 2013a, 2019). In the science classrooms, "entities or properties are brought into being or invented" (Osborne & Patterson, 2011: 629) during the process of explanation

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(etymologically, the act of spreading out, making plain) with the aim of providing a satisfactory account of a question, problem, issue, or situation under study. *Thus, providing a model of abduction that stresses its explanatory virtues seems to be a relevant contribution for science education.*

Following key authors of the last five decades (Flash & Kakas, 2000; Giere, 1991; Hintikka, 1999; Lawson, 2003, 2010; Magnani, 2001, 2017; Oh, 2012; Paavola, 2004; Park, 2015; Samaja, 2005; Thagard, 1978, 1988), we assume that abductive reasoning plays a major role in the production of science by scientists. Therefore, we present here the argument that abduction should be accorded central importance in science teaching: in the transmission of "normative" scientific explanations, in the teaching of scientific explanation and modelling as competences, and in the treatment of what is called the "nature of science" (NOS)—especially in regard to "gaining a proper understanding of the nature of explanation" (McCain, 2015: 827).

The first systematic investigations into abduction are due to the American philosopher Charles S. Peirce (1839–1914). As it is well known, he was the pioneering scholar in embarking in a serious recovery of Aristotle's idea of "apagōgḗ" (ἀπαγωγή), developed in his *Prior Analytics* (Aristotle, 1964: An. Pr., II, 25, 69 a 20–35). It is Peirce's insightful identification of the significance of such a notion *for a complete characterisation of the nature of science* that has provided all the foundational elements that shape the contemporary debate around abduction:

> This step of adopting a hypothesis *as being suggested by the facts*, is what I call abduction. I reckon it as *a form of inference*, however problematical the hypothesis may be held. What are to be the *logical rules* to which we are to conform in taking this step? There would be no logic in imposing rules, and saying that they ought to be followed, until it is made out that the purpose of hypothesis requires them. (Peirce, 1931-1958 [1901]: CP 7.202; emphases added)

Peirce wrote extensively on the subject and provided several complementary definitions of abductive inference, with different degrees of generality and abstraction. However, what can probably be considered his "canonical" approach presents it, in his mature publications, under the following form: "The surprising fact, C, is observed; but if A were true, C would be a matter of course. Hence, there is reason to suspect that A is true" (Peirce 1931–1958 [1903]: CP 5.189).

This well-known characterisation of the "abductive syllogism" is based on the template provided by the Mediaeval nomenclature of *induction* and *deduction* (see Table 1), which makes use of the Latin verb "ducĕre" ("lead", in the sense of conducting from premises to conclusions). For this reason, the historical portrayal of abduction in Table 1 results formally equivalent to the classical *fallacy of affirming the consequent* within monotonic logic (Aguayo, 2011). This syllogistic form has been deemed fallacious because "demonstrative" logic excludes propositions inferred on the basis of the recognition of *possibility*. Classical logic has centred on the *necessity* of deduced conclusions and the *probability* of induced conclusions; abductive logic takes a step forward by introducing the notion of *plausibility* of "possible" propositions, thus incorporating some elements of the psychology of inference.[1] As seen in Peirce's quotation

[1] As a "third way" in the traditional association of deduction with necessity and induction with probability, Peirce recovers Aristotelian abduction construing it as the process of possible inference (cf. Shook 2016, and for the notion of "strength" of such an inference: Peirce 1931-1958 [1903]: CP 5.180-212). In the Peircean framework, abduced conclusions are plausible (weak) and "pursuit-worthy" (i.e. they should be further investigated). From a pragmatist point of view, they lead to *courses of action*. We thank an anonymous reviewer of our article for their insightful suggestions towards the phrasing of these distinctions.

Table 1 Syllogistic characterisation of abductive inference, contrasted to deduction and induction.Adapted from Peirce (1931–1958 [1878]: CP 2.623)

Deduction	Induction	Abduction
Rule: All the beans from this bag are white. *Case:* These beans are from this bag. *therefore* *Result:* These beans are white.	*Case:* These beans are from this bag. *Result:* These beans are white. *therefore* *Rule:* All the beans from this bag are white.	*Rule:* All the beans from this bag are white. *Result:* These beans are white. *therefore* *Case:* These beans are from this bag.

above, in abductive reasoning, a conclusion ("hypothesis") is *suggested* by the premises ("facts") to a cognitive agent making the inference.

In the twentieth-century philosophy of science, opening the door to abductive reasoning comported allowing it simultaneous participation in the famous contexts of *discovery* and *justification*, established by logical empiricism. Thus, "abduction can be both a component in the discovery of hypotheses and a key ingredient in their justification" (Thagard, 1988: 52).

But offering a compact and satisfactory definition of abduction, or of abductive reasoning, remains to this day one of the central challenges in the contemporary scholarly debate around scientific inference (Mcauliffe, 2015; Nepomuceno-Fernández et al., 2014; Park, 2015). Consequently, characterisation of abduction has become a key concern in the depiction of the nature of the scientific methodology, with undeniable implications for science education.

Of course, it is possible for the aims of this article to operate with the general idea that abduction refers to a type of inference that consists in "selecting or inventing a hypothesis that explains a particular empirical case or set of data better than any other candidate hypothesis, as a provisional hypothesis and a worthy candidate for further investigation" (Thornberg & Charmaz, 2014: 153). This characterisation of abduction, rooted in Peirce's formulations, mentions the two actions of *selection* and *invention* of hypotheses, also included in the definition of scientific explanation to which we adhere in this article. To these two actions, we could add those of *activation*, *application*, *justification*, and *evaluation* (compare with Magnani, 2016).

However, rather than clinging to the technical meaning of each term of the previous phrases, it is sufficient for our purposes to pay attention to their overall structure so as to capture the gist of abduction. Indeed, these first-order, encompassing attempts at defining abductive reasoning that we have provided try to convey vital features of the current theoretical conceptions on this intellective process. At the same time, they hint at the complex historical development of these conceptions, calling for the establishment of an *archaeology* of abduction, and demand for a moderate positioning, or "third way", in the current debate around them, in what we see as an elucidation of its *epistemics* (that is, the mechanics of its functioning in processes of theory production).

In the following section, we delve into these two matters to produce a reasonable, minimal characterisation of abduction for school science of pragmatic and contextual nature. This twofold strategy that we adopt entails the use of a diversity of classifications (cf. Park, 2015). In order to perform what we call archaeology of abduction, we go back to the very "creators" of the idea: Aristotle, responsible for its classical formulation, and Peirce, author of a modern, pragmatist revisitation. And, for what we call epistemics of abduction, we deem it necessary to draw on material from the two models that nowadays define the debate around it: the so-called AKM and GW schemas. Such schemas are reviewed in the following section, on the one hand, to show the evolution of the theoretical discussion around abduction and, on the other, to support our choice for *contextualisation* of abductive reasoning (as performed, for instance, by more recent eco-cognitive models proposed in response to the debate). Thus, a "contextualised" approach to abduction is presented considering elements of the AKM and GW schemas that seem most appropriate for science education.

Our motivation for using a contextual perspective is the need to introduce more semantic and pragmatic considerations into the AKM and GW schemas during the process of adapting and combining some of their features for teaching science and the nature of science. As it will be seen, it is our contention in this article that a more general conception of abduction permits bypassing sophisticated technical problems without sacrificing conceptual rigour. Importantly, a contextualised perspective allows minimising the complex issue around the "degree" of *explanationism* in abductive reasoning, a desirable virtue if we take into account that, in the domain of science education, authors strongly suggest that school scientific activity can be understood as the construction of plausible explanations for puzzling phenomena (Eder & Adúriz-Bravo, 2008; Izquierdo-Aymerich & Adúriz-Bravo, 2003).

2 In Search of a Model of Abduction for Science Education

In our view, a key aspect to be considered when constructing a working definition of abduction for science education deals with differentiating it from induction,[2] which is a mode of inference much more extensively studied from classical logic and much more frequently used in historical and educational depictions of the scientific method (see, for instance, Rothchild, 2006 and, in contrast, Medawar, 1963). Alarmingly enough, when it comes to school science, many of such inductive depictions have retained the dogmatic flavour that was ubiquitous before the so-called new philosophy of science of the 1950s and 1960s confronted the naiveté of their image of how scientists work. The monolithic character of the "received" conception of method is apparent in this relatively recent instructional material:

> The inductive method (*usually called the scientific method*) is the deductive method "turned upside down". The deductive method starts with a few true statements (axioms) with the goal of proving many true statements (theorems) that logically follow from them. The inductive method starts with many observations of nature, with the goal of finding a few, powerful statements about how nature works (laws and theories). […] In the scientific method, observation of nature is the authority. If an idea conflicts with what happens in nature, the idea must be changed or abandoned. (Stanbrough, 2009: n/p; emphasis added)

[2] According to Woosuk Park (2015), this may have been the driving force of Peirce's monumental studies on abduction.

The distinction between abduction and induction that we want to explore needs to deal with the fact that both modes of inference are usually located in the realm of *non-monotonic* reasoning—i.e. that sensitive to the addition of premises, which alter the content of the conclusions—and of *ampliative* reasoning, i.e. that in which the content of the conclusions goes beyond what is implicitly contained in the premises (Levi, 2005). This foundational family resemblance might have been the source of the most usual confusions and conflations between the two, which led either to their assimilation or to the erasure of abduction in favour of induction (see, for instance, Park, 2015).

In accordance with the arguments developed in this article, we suggest that induction can be considered "mildly" non-monotonic and ampliative (contrast with Levi, 2005), whereas the power of abduction for the production of science would lie in its *marked* non-monotonicity and ampliativeness as an inference. The idea of monotonicity, which in part borrows its technical meaning from mathematics, could be in principle extended to refer also to those non-necessary inferences that maintain or preserve an "inductive" relationship (here understood *lato sensu*, as cumulative and generalising) with the bulk of the inferrers' epistemic "stock" (i.e. their accumulated knowledge background).[3] In contrast, we want to introduce the notions of "marked" non-monotonicity and ampliativeness, which can be predicated of pieces of reasoning that draw *very defeasible* conclusions from *very incomplete* information (see Magnani, 2001: 23).

Missing, overlapping, or diluting monotonicity and ampliativeness as relevant axes for distinction left induction and abduction at opposite sides of the fence when the scientific contexts of discovery and justification were demarcated in the 1920s. The "received view" on scientific inference in mainstream philosophy of science firmly based justification on the value of "measurable" probability of induced conclusions, banning the more "intangible" value of plausibility of abduced hypotheses to the study of scientific creativity, thus stagnating—for over four decades—methodological discussion. If we introduce degrees of monotonicity and ampliativeness into the picture, induction can be said to work more conservatively on the general traits of data (i.e. their conforming a *pattern*), while abduction would be focussing more boldly on ascertaining their specificity (i.e. their belonging to what in Table 1 is labelled as "rule") *through the introduction of novel concepts* to make sense of data. Thus, as we will contend in this article, our approach to abduction gives relevance *to its undoubted explanatory value* (or "virtue") in experimental and natural sciences.

The recognition of the long-hauled and unfair dismissal of abduction from orthodox accounts of the nature of scientific thinking prompted, in the second half of last century, its gradual philosophical recovery, enriched from a number of disciplines besides logic (argumentation theory, history of science, cognitive science, social studies, computer science, artificial intelligence, etc.). In recent, *naturalised* philosophy of science, two different positions on abductive reasoning emerged, known as the "AKM" and "GW" schemas, according to the acronyms composed with the surnames of their main supporters (Aliseda-Kowalski-Kakas-Kuipers-Magnani-Meheus and Gabbay-Woods, respectively: Park, 2015).

The opposition between these two models is the source of a number of classifications that we take as starting points for the proposal in this article, and this is why we want

[3] Classically, knowledge acquired through experience would be considered the core of that background, but it only constitutes a part of the whole cognitive dimension, which also encompasses emotions, feelings, beliefs, expectations, judgements, etc. All these elements of course "load" the inferential mechanisms in the agents, and this particularly holds in the case of reasoning directed towards the recreation of scenarios.

to review them. *The core of the dissent between them arises when they want to ascertain whether explanation should be taken as a characterising goal for abduction.* The AKM model considers this mode of inference as an (or perhaps *the*) essentially “explanatory” argument (a position that we find extremely rich for science education), while Gabbay and Woods contend such explanationism and introduce nuances, constraints, and expansions that we certainly need to take into account for our picture.

It is interesting to notice that these two main positions on abduction come from research areas where this mode of inference has been used as a key to solve what is called “ignorance problems”. Through abductive reasoning, basic ignorance around a situation—which does not need to be considered “total” ignorance—cannot be completely solved (and this would be a weakness of the AKM schema). Nevertheless, such ignorance is not left intact in the process (and this would in turn be a shortcoming in the GW formulation). According to the view sustained here, the abductive (as opposed to the inductive) process works as a *first-order* “ignorance-mitigating” accommodation of the problematic situation under consideration (Magnani, 2016: 95), where neither “subduance” of that situation by demonstrative explanation nor “surrendering” in front of it is an epistemic option to be considered by the inferring subject.[4]

Although ignorance mitigation is a common theoretical concept in both representations of abduction, there emerges a crucial difference in the way they operationalise it. In the AKM schema, the processes occurring during abduction lead to the hypothesis acquiring a status attributable to knowledge in a general sense (i.e. it helps to make meaning by “arranging” a puzzling situation). Accordingly, the examples proposed by the AKM supporters take the form of *diagnosis*: through abduction, an original way is generated to connect retrievable background knowledge with a particular hypothesis, posed in the light of the problem to be solved.

But this account leads to two technical obstacles: (1) it seems to be the case that not all ignorance problems can be reduced to diagnostic situations, and (2) it is clear that the proposition of a hypothesis does not mitigate ignorance to the point of eliminating its tentative status. There are several ways of testing hypotheses that do not necessarily lead to their corroboration, but such hypotheses prove viable for explanation even with their provisional nature.

In opposition, the GW schema argues that mitigation during abductive inference “preserves” a strong degree of ignorance in its classical sense. In this model, it is overtly recognised that the hypothesis always retains a provisionality that cannot be reduced through abductive mechanisms. According to these authors, in abduction, a hypothesis is *conjectured* to be subsequently tested, but this second phase implies moving towards mildly ampliative inductive patterns within a plan of *enquiry*.

In the previous characterisation, it can be noted that recent philosophy of science of cognitive orientation introduces a continuity between abductive and inductive mechanisms. This strategy has led to almost full identification of abduction with what is called “inference to the best explanation” (IBE). Although it is impossible for us to address such a delicate issue here (see, for instance, Tuzet, 2019), we have decided to highlight the existence of different *degrees* of (and perhaps even different processes in) ignorance mitigation. We can consider, for instance, that the “inductive way” leads to a conclusion that can be taken as knowledge understood as propositions predicated of a corpus of homogeneous

[4] Of course all these considerations are applied to the production of knowledge in general, but they can be smoothly transposed to scientific theorising.

data that can be tested, refuted, etc. The "abductive way", because of its marked ampliativeness, produces hypotheses of a much more tentative nature, on the basis of a much more modest input, but—in our view—mainly directed towards contributing with satisfactory explanations.

According to the previous depiction (cf. Sharpe, 1970: 24), abduction would be activated in the first place with the intention of mitigating ignorance by producing a plausible explanatory hypothesis, prior to the deployment of a collection of inductive inferences *stricto sensu* designed to put that hypothesis to the test. In fact, for there to be IBE-type mitigation, possibilities must have been previously proposed and founded. The constraints operating in the abductive phase ensure that a hypothesis reasonably fits the situation under investigation; in the phase of (inductive) IBE, the formalised hypothesis is more systematically contrasted with a network of available knowledge.

We must bear in mind that the AKM model was formulated within the framework of research and development on logic and mathematics, while the GW schema is one of the first overtly cognitive approaches to "productive" reasoning. These significant differences between their *contexts of enunciation* have a bearing on the previous discussion and, consequently, on our didactical review. Indeed, the AKM model has become connected with "pre-inductive", hypotheses-based processes, which assimilate abductive reasoning to diagnostics in its broadest meaning and bring it closer to model-based reasoning (Adúriz-Bravo, 2019; Hoffmann, 2011), a depiction to which we want to strongly adhere. The GW model, in its turn, has been identified with the more creative generation of knowledge *accommodations* in processes of adaptation to novelty, and this cognitive perspective is for us valuable in understanding learning processes in the science classrooms.

Of course, both reconstructions of abduction share the aim of finding its logical form (Park, 2015): abstracting it as a formal object of knowledge, detached, as much as possible, from its pragmatic contexts of occurrence. In the AKM and GW models, inferential agents are considered a "Canopic jar" (in the sense that their integral cognitive dimension is not taken into account in the explanation of inference, as indicated in Note 3), supporting systems of more or less *neutral* inferential processes, as portrayed by logical empiricism.[5] Importantly for our arguments, both reconstructions—with several technical differences—have also converged in a characterisation of abduction that recognises for it the two separate, yet complementary, functions that we cited above: hypothesis generation (nowadays customarily called "fill-up": Park, 2017), and selection (conversely, "cut-down").

For the educational considerations in this article, it results unnecessary, and may even prove confusing, to introduce the whole system of *syntactic* (i.e. formal) mechanisms postulated in the sophisticated logical descriptions of the two models of abduction (see Magnani, 2016: Appendix A, for an overview). It is enough to say that, in the case of the AKM schema, the reconstructive strategy implies incorporating an abductive "leap" in the last steps of an implication chain, resulting in the generation of a hypothesis as a "non-classical" consequence, that is, a statement that *adds* information that transcends inductive patterns and introduces a new "state of affairs" to be considered. In order to understand this, let us examine under the light of the AKM framework another famous neo-Peircean example (see Samaja, 2005).

Let us consider a possible inference ascending from "Mark always wears blue shirts" to "Mark is a bus driver". Such a piece of reasoning can be recognised as markedly

[5] A discussion of the consistent neglect of psychological, ethical, aesthetic, etc., elements in the writings of mainstream logical empiricists can be found in Putnam (2002: chapter 1).

ampliative by virtue of introducing a new conception that was not part of the inductive basis. An instance of abduction like this one reconstructed with the AKM apparatus becomes a non-classical (or, as one of us has labelled, “para-logical”: Adúriz-Bravo, 2014, 2015) syllogism, because its conclusion does not come *directly* from stabilised pieces of knowledge. It rather proposes an explicit connection of a puzzling enigma (Mark`s wardrobe) with some of the available background information (on Mark’s lifestyle) that is deemed as “possibly pertinent” to ascertain Mark’s job. This characterisation of abductive reasoning shows obvious links to the pragmatist approach in the Peircean tradition and focusses on what is called its “tentative element”, meaning that the abduced conclusion establishes a new way of provisionally managing uncertainty or ignorance and of operating in consequence.

Authors in the GW faction, in turn, criticise this concept of tentativeness in AKM as an attempt to hide the fact that their schema remains “consequentialist” (Gabbay & Woods, 2005: 48–50), aiming at explanation by subsumption. According to the alternative schema that they propose, abduction is formally portrayed *as a rapid search for reconciliation* between the experiential background already possessed by the subject and an event that requires “resolution”. For instance, if you decide not to take a particular street at night based on your sighting of some individuals there, abductive reasoning triggers a change in your beliefs and actions on the basis of a mere conjecture, a “possible world”.

Thus, the reconciliation between problem and solution that ensues abduction probably has as its main function *establishing new courses of action*, and this is an idea that we want to recover for our didactical “transposition”. Abduction “finishes” with the generation of a hypothetical conjecture that gives way to (founded) action (Gabbay & Woods, 2005: 48–50). As stated before, the process that follows this initial phase of “conjecturing for reconciling” would be a series of *inductive inferences*, since, according to this schema, a high degree of ignorance will no longer be preserved in front of the now *intervened* event.

The GW schema, by stressing the fact that tentativeness breaks consequentialism—and hence explanationism—wants to show that the rival AKM formulation does not allow for a satisfactory distinction between epistemic and cognitive elements and therefore poses problems of “translation” into a (semi-formal) logical representation. In the *abductive process* of the GW inferential chain, there may be a restricted component of ignorance mitigation, but the hypothesis retains its marked provisionality seen under the classical sense of certainty—or at least of corroboration. At the same time, there is a change in beliefs and actions operated by this kind of reasoning.

In John Woods’ words: “in a full abduction, [hypothesis] H is activated by being released for inferential work in the *domain of enquiry* within which the ignorance-problem arose in the first place” (Woods, 2013: 371; our emphasis). For him, conclusions are not abduced to successfully overcome ignorance but to trigger inferential processes; they retain a strong conjectural status along the process (Magnani, 2015: 288).

2.1 *An Epitome of In Vivo Abductive Inference*

Let us now examine in some detail an example (based on true events narrated by a philosophy teacher!) that appears as a candidate of epitomic abductive reasoning and will therefore result useful at several points of our discussion. We have used this example many times within didactical sequences addressed to secondary and university students and teachers (Adúriz-Bravo, 2021; Sans Pinillos & Adúriz-Bravo, 2021).

Imagine that, while travelling on the metro, you see two young men heatedly arguing at one end of the carriage. We have to consider that, in such a situation, the only information on the event that you have is visual (since you are too far away from them to overhear their verbal exchange), and even that may be fragmentary, since the two individuals might appear and disappear from your sight because of other travellers blocking the view. Under these conditions, you might *abduce* one (or more) of a number of different conjectural, or *hypothetical*, conclusions with the aims of explaining the situation and eventually taking courses of action. For instance, you might think that the two men are fighting over a woman who both are interested in, that they have been drinking and now a petty disagreement has gone out of control, etc.

Your inferred (and therefore your discarded) solutions—under the form of "possible scenarios"—to the puzzle posed by the enigmatic nature of the scene are prompted by its constituent elements (it is definitely a row, but what *kind* of a row?). But they are also heavily influenced by the context. For instance, you will probably ponder the hypothesis that this is a dispute over money only if you consider such matters "discussable" in the public transport in your own country, or, if the scene is set in certain big cities in Latin America, you could open your mind to the bizarre possibility of mapping it onto an artistic performance—the two young men are amateur actors entertaining the passengers and seeking for their monetary collaboration. The strikingly diverse nature of the explanation candidates that you abduce, not at all expectable in inductive reasoning, is at the core of our notion of marked ampliativeness.

Then imagine that you get too curious, or even worried because of the exalted nature of the confrontation, and you decide to take action; as you get closer and closer to the individuals, it becomes possible for you to hear some of the words in the dialogue. The reactions of the other passengers in the vicinity of the "fighters" can also contribute to your process of *hypothesis* as understood by Peirce. These new sources of information could now point at a result *completely at odds* with your previous interpretations of the scene (and here emerges what we have classified as marked non-monotonicity in the abductive piece of reasoning under construction): you begin to suspect, for instance, that the two men are a couple (in the sense that they are romantically or sexually associated) and that the dispute is of domestic nature.

In this "miniature" example of *in vivo* inference, which can be safely reconstructed as abductive reasoning, all the conceptual elements that we need for a good *educational* definition are present. Hypothetical reasoning is here triggered by ignorance (or rather, by the urging need to mitigate it): missing information transforms a plain set of trivial facts during the journey back home into a discordant event that *surprises* us all as observers, and this "prompts us to generate an explanation [since it] would be pointless to waste mental resources on something ordinary or expected" (Thagard 2007: 227). We can thus highlight the fact that abduction is a kind of reasoning effectively *directed towards problem-solving*, taking into account that problem-solving is a standard characterisation of school science in recent educational accounts (Alberida et al., 2018). In the literature of didactics of science, this process is often portrayed as the production of a "school scientific explanation" (Adúriz-Bravo, 2019, 2020), hence our interest for elucidating the participation of abductive reasoning therein.

The mechanisms activated in order to complete the missing pieces of information *that can give coherence to the scene* are of marked ampliative nature: the inferrer is not just "inducing" on the edge of their observations. Hence, the proposed solutions remain with tentative epistemic value (unless a more serious corroboration is attempted). Additionally, the possibility of emergence of one or other hypothetical explanation relates to the context of reasoning via multiple social and cultural constraints of our epistemic apparatus. In this case, skipping the possibility of a "marital" interpretation can be a classic case of bias or prejudice. Similarly, in science teaching, we work with modelled explanations on natural phenomena that are *situated* and background-sensitive, sometimes prove "misconceptual", compete with one another, and need to be put to the test.

The iterative "auto-correction" process that begins when you decide to get closer to the scene, in turn, unveils the already mentioned markedly non-monotonic nature of this chain of inferences: the new information that you collect does not "pile up" with the initial premises but prompts instead a complete transformation of the conclusion. Lastly, the first part of the example depicts the process of fill-up: a variety of hypotheses come to our aid when trying to make sense of the situation, whereas later on, our detective attitude of finding out more information to give strength to one or other possible interpretation can be modelled as the process of cut-down. These same two processes occur when constructing school scientific explanations that are based on models from the experimental or natural sciences (or even from common sense or folk knowledge).

From the point of view of the AKM schema, our example is a rather sophisticated case of what the Mexican philosopher Atocha Aliseda (2006: 29–30) calls common-sense abduction,[6] which, in her own account, leads thinking *from evidence to explanation*. Under the light of this schema, this kind of reasoning operates with a *principle of economy*: the inferring agent swiftly selects facts, establishes connections, computes options, minimises contradiction, and reaches hypothetical conclusions of recognisable explanatory value.

If seen from the viewpoint of the GW schema, our example remains strictly abductive only in the first stages, where a process of knowledge *extension* to adapt to novelty is occurring. When a higher degree of corroboration is sought, new possibilities of obtaining results emerge from the use of more conservative induction (or, alternatively, *analogy*). In the GW schema, abduction loses relevance once a viable hypothesis has been foundedly conjectured and begins to be investigated more seriously (Gabbay & Woods, 2005: 47). This second phase would correspond to Peirce's idea that an abduced conclusion *is a worthy candidate for further investigation* (Thornberg & Charmaz, 2014; Yu & Zenker, 2018).

2.2 Drawbacks of the AKM and GW Schemas for Science Education

A first problem with directly incorporating these two famous approaches to abduction into science education lies in the fact that they may lead to a dead end due to their "substantialist" stance: they seek for some characteristics of abduction that are supposedly intrinsic and essential. The AKM schema considers that explanationism is a constitutive condition of any successful abduction (Aliseda, 2006: xii): the abduced hypothesis has as aim properly explaining a puzzling situation. In contrast, the GW schema does the same with the requirement of ignorance-preservation (Gabbay & Woods, 2005: 48–49): the abduced hypothesis is produced only as a conjecture to accommodate puzzling novelty. Blind alleys appear when we attempt at fruitful transference to our field because the AKM schema sees explanatory character as an essential trait to differentiate abduction from induction and the GW schema makes no special effort in distinguishing these two kinds of reasoning

[6] Aliseda (2006: 29–31) identifies abduction in a variety of typified situations: common sense problem-solving, diagnosis, statistical reasoning, and scientific modelling. Medical diagnosis can in itself be reconstructed as an elaborate example of statistical reasoning (p. 29), while scientific discovery would involve producing an explanation "with respect to some body of beliefs" (p. 30) and trying a diversity of options.

patterns, seeing them just as progressive mechanisms in ignorance mitigation, and these two choices can quickly blur the specificity that we want to attribute to abductive thinking—that arising from its marked ampliativeness. Such a property is, in our view, key for our didactical reconstruction of scientific inferences—and of the school scientific method altogether.

If we apply the principles of the GW schema to our "metro example", abduction would close when one of the troubled traveller's conjectures (in the real anecdote, the "marital" conjecture) acquires the status of a hypothesis under proper research, which needs planning a series of actions (approaching the young men, looking at other passengers' reactions, "interpreting" not only the content but also the rhetoric and context of the conversation, etc.). Accordingly, if we want to understand our example under the light of this model, some portions of it would probably lie *outside* abduction *stricto sensu*, because active search for new information is enough to transform the status of our abductive hypothesis into a classical inductive proposition.

Additional problems appear when we want to transpose these characterisations to educational research. The AKM schema, concocted in the debates in logic and computation around the representation of human reasoning, may prove of restricted usability, since it does not exhaust the whole definition of classical, Aristotelian and Peircean abduction, understood as the establishment of productive *rules* of some kind—this being the mechanism that we want to explore for science education, since it fruitfully connects abductive inference with models (Adúriz-Bravo, 2019, 2020). Additionally, although an explanation-driven account obtained applying the AKM model could be safely used to map the cut-down phase of abduction in the science classrooms, perhaps it could not fully explain its more creative aspects, in the fill-up counterpart. In the "metro example", the AKM schema does not provide enough elements for us to understand how the actual scene occurring in front of us is mapped against "virtual scenes": what elements make the mapping pertinent? And therefore, what elements turn the abduced scenario "explanatory"?

Following the AKM schema, the abduced outcome "this must be a macho fight" is obtained as a first attempt to explain the row. According to this view, when the product of abduction is adopted as hypothesis, it is considered that it can play the same epistemological role as an explanation. Therefore, in a way, it has helped to mitigate ignorance around the puzzling situation: it has subsumed it under the general class of "fights". But the abduced result is provisional, so it can only play "as if" it was a piece of knowledge in the classical sense (in fact, the observer could get off the train in the next station without obtaining new information, carrying with themselves the wrong idea that this was a macho fight). This is the point where the non-explanatory account of abduction provided by the GW schema may be of interest: the highly provisional hypothesis conjectured through abduction disposes the subject to act in particular ways: it opens what we have called "courses of enquiry".

If the observer proceeds with their "investigation", they will acquire new pieces of information that may help to "arrive" at the hypothesis that both men are a couple and that the witnessed scene is nothing but a (typical) couple discussion. During this testing phase, the conjectured hypothesis works as a candidate-to-explain that can be effectively defended and may get more and more plausible (or, on the contrary, be discarded altogether after a non-monotonic accommodation of premises).

The GW schema seeks to solve the problem around the explanatory virtue of abduction by introducing induction in the moment when a hypothesis or conjecture needs to be tested more seriously. But the price to pay is restricting the autonomy of abduction in the overall epistemic process: it becomes ancillary to the classical inductive-deductive method.

According to Woods (2013: 371), "if [hypothesis] H goes on to test favourably, it may then be released for subsequent inferential engagement. But that is not abduction. It is induction". But this restrictive characterisation is at odds with the identification of abduction with apagoge and hypothesis, which we find extremely powerful for science teaching.

In our opinion, the "internal" dynamics of these problems and solutions in the contemporary logico-cognitive controversy does not contribute much to support the educational value of abduction, as the possibilities of increasing our scientific knowledge on the world via this mechanism are partially blurred in both reconstructions. Woods himself recognises this as a serious objection, since "there are real life contexts of reasoning in which such conservatism is given short shrift, in fact is ignored altogether" (Woods, 2013: 371). Among these contexts, the author mentions criminal trials and common sense reasoning, two "spheres" of human action that we want to connect with "school scientific enquiry" (Adúriz-Bravo, 2020, 2021).

It is important to notice that Woods' position would imply for us not only that an isolated, "pure" abductive syllogism is an entelechy in real life, but also that each of the successively chained abductive inferences is not at all autonomous from the rest (as in our example above). These results appear as a consequence of sticking to the condition of ignorance-preservation as indispensable in abduction. In this theoretical framework, inference to a strict explanation would then be an inductive ascent (Yu & Zenker, 2018).

But denying the autonomy of abduction would entail falling into a caricature of little teaching value of the classical taxonomy of abductive reasoning as the "third way" between deduction and induction proposed by Peirce in his early writings. And a limited characterisation of abduction would not permit us to understand, at the same time, processes such as discovering and identifying a rule from others that we want to make more conscious and structured in science education—such as *formalising*, *evaluating*, and *justifying* the rule. In our example, the "resolution" of the episode as a piece of abductive (rather than inductive) reasoning can be modelled as a complex, conscious, self-corrective process on the first inferred, prejudiced conjecture. Thus, following Aristotle and Peirce, we want to consider the whole process as abductive in order to derive useful implications for the teaching of the nature of the scientific method.

As a consequence of our previous considerations, it seems necessary to review how the AKM and GW models for abductive reasoning relate to Peirce's seminal characterisation and its Aristotelian roots. On the one hand, one of Peirce's most relevant achievements was to dissociate an abductive syllogism as a process from the success of its product—the arrival at a "true" conclusion.[7] In this sense, a hypothesis "may lead us to expect some facts to be *as they are*" (Peirce 1931–1958 [1901]: CP 7.202; emphasis added), but at the same time "may lead us in the future to *erroneous* expectations about other facts" (Peirce 1931–1958 [1901]: CP 7.202; emphasis added). Peirce identifies this property in "Eureka-like" reconstructions of historical cases—beginning with classical astronomy[8]—in which abduced hypotheses could only be adopted *through and for* testing.

On the other hand, Peirce's pragmatism works with a notion of hypothesis that falls not so far from the canon of analytic philosophy, and this permits a solid connection with the study of the "school scientific method". A Peircean hypothesis becomes more *reasonable* for scientists when it has the epistemic virtue of seeming "more real" in terms of correspondence with an expected underlying, law-like truth; this adjusts to a moderately *realist*

[7] For a distinction of process and product in abductive reasoning, see Aliseda (2006: 32–33).

[8] See, for instance, Hanson (1958), Thagard (1988), Aliseda (2006), Sans Pinillos (2017); Rivadulla (2018).

conception of school science, which for us has enormous formative value (Adúriz-Bravo, 2004; Izquierdo-Aymerich & Adúriz-Bravo, 2003).

2.3 Recovering the Core of Peirce's Abduction

Explaining the complexities and subtleties of Peirce's full characterisation of abduction—developed in writings spanning for five decades (see Fann, 1970)—far exceeds the possibilities of this article. For this reason, we find it appropriate to adopt Kapitan's (1997) brilliant reconstruction of Peirce's main theses on "scientific" abduction, adapted to science education, as a starting point for our theorisation:

1. *Thesis of autonomy.* In the pragmatist framework, there remains little doubt that abduction is a kind of reasoning that is definitely *distinct* from, and *irreducible* to, deduction and induction. This result, which Peirce claims as his "discovery", stems from a naturalised approach to the study of inference in contexts of problem-solving that resist an inductive-deductive reconstruction (we will expand this idea for the particular context of archaeology in thesis 4). In accordance with this first thesis, a characterisation of scientific thinking in science classes that does not explore the mode of inference proper of diagnostics, forensics, or the work of detectives and investigators will be epistemologically thwarted.
2. *Thesis of inference.* Scientific abduction is an (perhaps the?) inferential process of production of apparently new knowledge. This is Peirce's interpretation of Aristotle's inclusion of apagoge as a third syllogism, and not as a fallacy proper. The recovery of abductive reasoning is necessary for the pragmatic programme to minimise the ability of deduction and induction to produce genuinely productive hypotheses (akin to Popper's *bold conjectures*). In accordance with this, no robust account of the scientific methodology could be elaborated for science teaching if hypothetical (and model-based) reasoning is disregarded or deflated.
3. *Thesis of purpose.* The purpose of scientific abduction is both to generate new hypotheses and to select hypotheses for further examination. This thesis contains Peirce's early recognition that abduction comprises both fill-up and cut-down. Hence, a central aim of abductive reasoning in science would ultimately be to suggest innovative *courses of research*, an aim that is not completely fulfilled by purely deductive or inductive processes. This characterisation of the purpose of abductive reasoning is, in our view, inescapable in a satisfactory portrayal of school science as *enquiry* (Adúriz-Bravo, 2020).
4. *Thesis of comprehension.* In a maximal view, scientific abduction encompasses most of the operations through which theoretical knowledge is engendered in natural and experimental sciences: "All the ideas of science come to it by the way of abduction. Abduction consists in studying facts and devising a theory to explain them" (Peirce 1931–1958 [1903]: CP 5.170). Scientific "investigation" (i.e. the phase where scientists follow "vestigia": traces or footsteps) cannot be fully understood except in terms of this abductive devising of theoretical models. For example, at the heart of archaeological practice lies the need to reconstruct *vivid* possible and plausible scenarios in order to make sense of the remains found (Shelley, 1996). Lifestyle in antiquity is neither deduced nor induced from the excavation data. The production of shared theoretical knowledge via these mechanisms described by Peirce should precisely be the guiding force of school scientific modelling (Adúriz-Bravo, 2020).

As it can be seen, this reconstruction of the Peircean theses resorts to semantic categories (in logic and semiotics), and does not demur in "gnoseological" intricacies. The context of development of Peirce's ideas was American pragmatism at the turn of the century; he worked starting from Aristotelian logic, which did not distinguish between logical and psychological aspects in human reasoning processes (Sans Pinillos, 2021b). However, since Frege's (1956) formidable proposal to separate those, along with the tradition that follows it, nowadays we need tools to capture the logical elements in school scientific reasoning that prove rather separable of "hard" cognitive considerations. Revisiting an idea that we have already examined in this article, the epistemic state of ignorance can be seen as partially overlapping with the cognitive state of surprise. From a *contextual* perspective on abduction (such as those present in the so-called eco-cognitive models, which we will mention below), surprise can trigger a particular type of knowledge interactions that generate opportunities for founded action (Arfini, 2019). But, independent of the fact that such intricate cognitive phenomena live in classroom environments, we want to describe and analyse pieces of reasoning as texts, isolating them from the underlying mechanisms in students' minds but situating them in their context of production.

Many factors determine human behaviour, most of them uncontrollable at best or even poorly known. This fact evolves into a gap when the objective is to construct *naturalistic* representations of human reasoning with logical tools. There is undoubtedly a methodological lack in the theories for school science; one way of solving the problem could be to stretch our idea of abduction, on the one hand attempting at solving the blind-alley problems shown above and, on the other, considering new theoretical aspects (coming from the contemporary debate around abductive reasoning) that may lead us back to basics.

An attempt at theoretical expansion that may prove more respectful of the spirit of Peirce's ideas is provided by contextual models of abduction; among them, "eco-cognitive" (EC) models of abduction such as the one proposed by the Italian philosopher Lorenzo Magnani (2017) seem useful. EC-models attempt at solving the tension between explanationism and preservation of ignorance by placing inference in the context where it deploys, with all its interrelations (and hence the prefix "eco-"). This kind of models clearly *situates* the problem in question and the agent facing it (in our case, students in a science classroom). From this perspective, it is possible to understand that an action is determined and allowed by our inferential machinery plus our relationship with the environment.

The purported advantage of analysing abduction from a contextual perspective is that it lets us see the compatibility of some of the theoretical suggestions of the two previous models that we have been discussing. The nature of abduction is conceived by us as *dependent on the contextual demands of the situation* under study. With what we learn from our attempt at an "encompassing" model, we are equipped with tools to offer a "panoramic view" of how and where different classical understandings of abduction can converge and even cooperate in science teaching (Fig. 1).

Contextualised abduction seems to be bundling together the AKM and GW approaches through including ignorance mitigation and explanation as some of the constitutive parts of human reasoning and examining the ways in which these occur in various pragmatic settings. This idea is at the foundations of our prospective diagram in Fig. 1. Current research on abduction has critically revised the connections between inference (in people's minds) and reasoning (in semiotic reconstructions). In school science, a possible connection

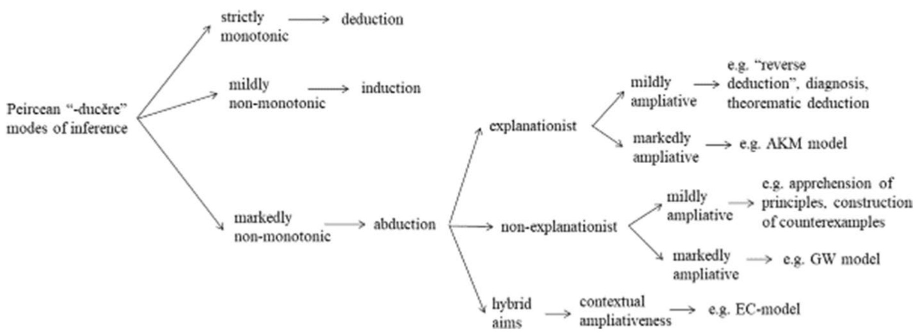

Fig. 1 Different interpretations of abduction that emerge from the use of the theoretical categories discussed in this article

between these two concepts can arise through the inclusion of the idea of *courses of enquiry* as a didactical counterpart of the pragmatic idea of action triggered by the products of reasoning (with a strong focus on explanation).

School scientific abduction can then be understood as a stylised reconstruction of an agent's inferential interaction with a disturbing situation that relies on the intellectual tools of that agent and on the "anchors" provided by the "non-disturbing", more familiar parts of the situation (extrapolate this to the example of Mark as a bus driver). The metaphor of "finding" a missing piece in a puzzle becomes suitable when a scientific problem shows to be genuinely enigmatic and calls for understanding (i.e. goes beyond a mere scientific "exercise"). The key element at stake here is the possibility that students recognise that they do not know something *on the basis of the same knowledge* that has not permitted them to "know" (understand) that thing.

Under this light, when doubt or confusion emerge in front of an elusive situation, hypotheses are generated as tentative answers, and the process of selection of one that has the virtues of being the most suitable *and* promising also starts simultaneously (and here lies our proposal for science teacher education: Sans Pinillos & Adúriz-Bravo, 2021). This more holistic and pragmatic model of abduction for science education, which can be epistemologically seen as a *contextualisation*, depicts the management of novelty as done through *decision-making*.

Following our diagram in Fig. 1, identifying explanation as the purpose of abduction in science does not necessarily couple with it being ampliative or not. Ampliativeness is turned into a contextual property determined by the characteristics of each area of knowledge in which we act. But our enquiry into the situation, which includes action, modifies the context. In Hintikka's (2007: 11) words, "[i]n real life we are both producers and consumers of knowledge".

The possibility of an abduced conclusion to be explanatory is subject to the contingent circumstances and the personal will of the agent who is trying to solve a scientific problem. Hypothesis-activation depends on the nature of the task. A purportedly "explanationist" piece of abduction can be seen as markedly ampliative, in our view where ampliativeness has degrees.

When facing novelty, our capacity of creating hypotheses predominates; after that, the context constrains the proliferation of such hypotheses through its material requirements. As shown in Fig. 1, it is in the last steps of reasoning when the process can be seen as mildly or markedly ampliative. Either theoretical frameworks are just "stretched" to account for the new phenomenon or they can be dramatically altered (and this is where the strongly non-monotonic character of abduction most clearly appears).

In our diagram, the AKM model should be understood as a process of formulation of a school scientific explanation that entails a more or less radical expansion of our background knowledge. An epitomic example of this situation that can be used in science education is medical diagnosis in "rare", sophisticated cases (such as the ones depicted in the TV series "House, M.D.", which we use as a "toy model" for scientific thinking). In these cases, diagnosis can be portrayed as a highly systematised process composed of a complex set of operations directed to collecting and *selecting* data from clinical judgement of a patient (Sans Pinillos, 2021a; Sooknanan & Seemungal, 2019). Such a situation can then be identified with the highly tentative, synthetic type of abductive reasoning that aims at explaining by subsuming (i.e. establishing the Peircean case-rule connection). In this process, a degree of uncertainty persists until the last stages (Sooknanan & Seemungal, 2019); this is product of the inevitable *interpretation* (and "inter-" here is a key element) that reconciles the established corpus of medical theory (or even new additions), objective data obtained from testing, symptoms that the patient during anamnesis claims to be suffering, and signs intentionally searched for to corroborate the latter.

Our characterisation of elaborate diagnostics as markedly ampliative explanatory abduction focusses on the fact that "diagnosers" have to be one step ahead of their theoretical background in order to understand the uniqueness of a rare case. In contrast, usual diagnoses in standard medical practice are much less ampliative in nature. For this reason, abduction operating in regular medical situations can be located in our diagram in Fig. 1 under the category of mildly ampliative cases of explanation. In these cases, the process of diagnosing could be reconstructed as a "warranted" kind of abductive reasoning, identified as "reverse deduction" and formalised with an economic version of the "para-logical" syllogism in Table 1. By "warranted"—and closely following Toulmin's (1958) argumentation theory—it is here implied that abduced hypotheses in many medical cases are strongly founded, for example, through standardised protocols (Sans Pinillos, 2021a). Here the context *constrains* the more creative and prolific aspects of hypothesising.[9]

According to our reconstruction, in this situation, more weight is given to finding similarities between patients and fitting the "new" instance to accepted knowledge, rather than to opting for more "creative" hypotheses from the beginning (and hence the famous saying "when you hear hoofbeats, think of horses, not zebras", for which American researcher Theodore Woodward of the School of Medicine at the University of Maryland is credited).

Transference of these ideas to school science can be done by making analogies between medical scenarios and famous historical cases in the "observational" sciences, such as "discoveries" in astronomy. Indeed, authors supporting the AKM schema equate to a large extent these two kinds of processes (Aliseda, 2006: 29–30); this makes it possible to discuss how much ampliative new pieces of astronomical knowledge result in their times. To what extent was Kepler's postulation of elliptical planetary orbits a big "leap forward"? And in the case of Le Verrier's suggestion of the existence of planet Neptune? In the first historical episode, what was the role of extrapolation from the mathematical description of the orbit of Mars as seen from Earth (Niiniluoto, 1999)? And in the second, how many

9 As opposed, for instance, to the more "divergent" process of *bricolage* proposed by the French anthropologist Claude Lévi-Strauss (1962), a process through which rather original mythological narratives are created.

alternative hypotheses could account at the time for the specific kind of perturbations recorded in the orbit of Uranus (Grosser, 1979)? Ampliativeness when modelling, as we have pointed out, is extremely dependent on practitioners' *epistemic commitment* to the corpus of accepted theories in a given scientific field.

In our diagram, in turn, a markedly ampliative abduction of initially non-explanatory nature can be mapped onto the GW scheme. This would be the case of the postulation of entities, relations, formalisms, etc. that prima facie do not serve the purpose of solving a puzzle that requires full hypothetical explanation but rather aim at unification (or sometimes reconciliation) of different scientific laws or models by means of *conjecturing*. In such cases, movement towards the explanatory step is understood as the beginning of a more conservative inductive cycle in which classical "experimental confirmations" are sought. Gabbay and Woods (2005: 121–122) reconstruct under this light Planck's invention of quanta as a requisite to arrive at a satisfactory law for black-body radiation. Following them, we could say that quanta in their original formulation should not be as much understood as a "state of affairs" explaining a problem but rather as a constraining condition holding together the structure of theoretical physics.[10]

Explanationist but mildly ampliative abduction can also be identified with what Peirce calls "theorematic deduction". Theorematic deduction (probably in connection with the notion of *enthymeme*), in contrast with classical, monotonic deduction, which is demonstrative, requires the use of auxiliary elements of support. This can be seen, for instance, in the abduction of mathematical "laws" from precepts and "general diagrams" in geometry (Magnani, 2001: 171), where the auxiliaries "explain" the nature of mathematical proofs in a process of "confirmation" that does not imply an extension of proven knowledge. In this kind of abduction on the border between formal and empirical sciences, semiotic relations of *iconicity* are created between auxiliary elements and structural forms (see Hintikka, 1998: 233). Iconicity, from the pragmatic point of view that we are adopting, basically refers to the fundamental semiotic relation of *similarity* between a sign and an object, which has sometimes been considered "natural" (cf. Dingemanse et al., 2020). Our approach includes this semiotic element to enable better comprehension of how the agents' positionings work when they try to understand their environment (Magnani et al., 2022).

Finally, when it comes to non-explanatory abduction that is only mildly ampliative, we could here recover cases in which abductive reasoning serves to characterise the kind of establishment of hypotheses that initiates processes of theorisation or formalisation. Aristotle, in his *Posterior Analytics*, develops the example of the apprehension ("intuition") of the "principles of science" (Aristotle, *An. Post.*, *II*, 19). In Aristotelian theory, any first step of (inductive or deductive) reasoning requires *pre-establishing* a set of premises or arguments that are not completely determined by the properties of the concrete piece of reasoning in which they will be used (in terms of inferability, necessity, monotonicity, etc.). In other words, these principles of science that define the mechanisms of demonstration, and their virtues and values, cannot be explained by the same

[10] Just as astronomy is the preferred arena to exemplify AKM abductions, atomic physics seems to be the discipline used to identify GW abductions (in further examples such as electron orbits or quarks). This curious trait of contemporary academic discussion can probably provide hints to understand the differences in the standard rhetoric present in didactical treatments of the aforementioned historical examples in textbooks and teaching.

demonstrative process in which they participate: they need a parallel track that is here identified as a process of apagoge.

We have also considered the case of the (probably) abductive construction of formal "counterexamples" in elaborate arguments (Hintikka, 1998: 232).[11] Strictly speaking, a counterexample is constructed—on the basis of auxiliary elements—in order to establish that a problem cannot be classically dealt with as expected. The process of identification and application of a counterexample is, in its first phase, the generation of hypotheses that are abductively proposed during fill-up as possible candidates against aspects of a claim. Then comes a second phase of cut-down when how some of those hypotheses could be put to work is evaluated. The "abduced counterexample" proposes a possible scenario in which the claim does not hold partially or totally; it consequently shows a course of action that is alternative to the one chosen up to that moment. Counterexamples, when they only modify the claim without implying substantial changes, would be, in our framework, the product of a non-explanatory, mildly ampliative abductive inference. Such counterexamples have to be introduced *and then explained* to make effect on their own (i.e. trigger the phase of trials); additionally, they have no "ampliative power" until their degree of novelty is assessed.

3 Implications for Science Education

Since Hintikka's (1998, 1999, 2007) proclamation that abduction should be considered the fundamental problem of contemporary philosophy of science, it has become standard practice to approach the logical and epistemological aspects of abductive inference using intellectual tools from different disciplinary areas (Park, 2015). In accordance with this, a multi-referential approach to the construction of what we have labelled "school scientific abduction" seems to us the most solid way for an effective integration of this mode of inference in science teaching. In this article, we have suggested that such an approach could include non-monotonic logic, modern argumentation theory, philosophy of science of the last four decades, and a recovery of some aspects of Peircean semiotics. All these referential frameworks have already been used, more or less extensively, in didactics of science and particularly in the field of the nature of science.

The lively academic debate that started in the 1990s around the participation of abduction in the two classical contexts of science—which we have developed in the previous section—owes much to Frege's ideas on how logic and psychology are (dis) articulated (Thagard, 1988: 7; Aliseda, 2006: 65; Hintikka, 2007: 17; Magnani, 2009: 287; Niiniluoto, 2014: 378). It also bases on a critical rejection of the ab initio split between analytic and synthetic modes of knowledge production (Putnam, 2002), as the one started after World War II by the new philosophy of science, which was also open to a variety of disciplinary influences. Undoubtedly, the main outcome of this cross-fertilisation has been moving forward from the positivistic conception of knowledge as verified propositions reducible to logical formulas. Such a move towards a more sophisticated view on the *validity* of scientific statements has also been central in didactical research and innovation (see Southerland et al., 2001).

[11] In Plato's (and from Socrates') work, counterexamples are explicitly identified as a formal tool for the then newly born philosophy, which should be used systematically in argumentation. The mechanics of "counterexample production" can be studied in areas as diverse as Euler's conjecture on the sum of powers and Wittgenstein's studies on the nature of "certainty".

Definitely leaving the "received view" on scientific explanation behind has shown the will of the learned communities to produce new ways of conceptualising contingent, heuristic reasons and arguments and to contest the incapacity of classical models to give satisfactory answers to the issues of novelty, creativity, and change in scientific research. A corresponding idea for science education that we take as our thesis is to consider abduction as a/the privileged mechanism of generation of original ideas; going deeper into this mechanism would make it possible to understand the very nature of the link between abductive premises and conclusions, in which something beyond sheer generalisation occurs. In terms of Paul Thagard (1988), during abduction a "projected truth" is generated. In school science, this tentative element of projection in the product of abduction would have value in the *plausibility* of the identified hypothesis to become a rule for the case on the basis of what Peirce calls the "result" (Table 1).

On the other hand, our detailed analysis on abduction was established around the opposition between explanationist and non-explanationist models (compare with Alchourrón et al., 1985; Aliseda, 2006; Magnani, 2009). This instrumental, pragmatic distinction between two points of view on abduction offered us with the opportunity to recover the (para-)logical perspective on this mode of inference, providing tools to study the nature of abductive pieces of reasoning (understood as "texts"). On the basis of the idea of abducing-to-explain, we ascertained that AKM abduction can be seen as the main inferential mechanism invoked to make sense of a puzzling phenomenon (Aliseda, 2006: 28) in science classrooms. From this theoretical perspective, abduction in school science can be defined as the collective "process of formulating a hypothesis which, if it were true, would provide an explanation for the phenomenon in question" (Clement & Núñez Oviedo, 2003: 2).

We also portrayed GW abduction as an intellectual procedure—and its textual counterpart—"in which something that lacks classical explanatory epistemic virtue can be accepted because it has virtue of another kind" (Magnani, 2017: 1).[12] The introduction of this second perspective required reconciliation with the philosophical frameworks of Aristotle and Peirce. The lesson that we learnt opened the possibility of abductive pieces of reasoning that could be directed to other aims than scientific explanation, but instances of this (see Fig. 1) seem to us to have only relative weight in science teaching, which is strongly characterised by the epistemic goal of explaining the natural world (Adúriz-Bravo, 2014; Eder & Adúriz-Bravo, 2008).

We then examined "contextual solutions" to these dichotomic interpretations, which appeared in different academic disciplines with the intention of solving the deadlock of the previous, long period of "definition" of abductive reasoning. The new solutions intend to tackle what they recognise as a major obstacle in standard conceptualisation of abduction: characterising it through a set of essential traits. They also eliminate the identification of explanation as the *differentiating* aim of abductive inferences.

In particular, Magnani's EC approach for contextualisation seeks to characterise the nature of reasoning directed towards *optimising* the use of resources put to meaning making understood as a human praxis (see Magnani, 2009). In his perspective, it is the actions of cognitive agents that arrange the abductively suggested lines of enquiry. However, it is

[12] In this article, we will not go deeper into the technical issue of the "virtues" that abduction shows for the inferrers (scientists, students), but we have already mentioned some of them that for us seem fruitful for science education. A clear example is that of *tentativeness*; abductive reasoning (in the contexts that we present as "analogues" for science) "keeps the trial open" until a satisfactory explanation emerges. This provides an image of the scientific method that is extremely formative for students (and for teachers!).

unnecessary to assume a solid commitment to the theoretical frameworks of cognitive science to apply his model to didactics of science. A more general understanding of the contextual perspective on abduction suggests paying attention to the influence that the environment has on "inferrers" and to the multimodal capacity of human resources to understand. The context is configured through the different ways of manipulating available resources, so that scientific propositions are linked to the possible actions that scientists abductively define to move forward under uncertainty.

Magnani (2017: 138–139) sees abduction as an extremely sensitive, constantly running mechanism of incorporation and abortion of information and of adaptation to an ever-changing environment. His model, and other contextual approaches, give us clues for the current debate around the issue of if abduction can be equalled to an inference to the best explanation (Harman, 1965) or to an "inference to the best available explanation" (IBAE) (Schurz, 2008). This debate, however, is not examined in this article, since we understand that the epistemics of school scientific explanation can be reconstructed without the technical distinctions that have been proposed (see Mcauliffe, 2015). There are, nevertheless, valuable antecedents analysing the place of IBE in science education that readers can refer to (Brigandt, 2016; Wilkenfeld & Lombrozo, 2015).

Profiting from the consequences of considering contextual models, and recovering Aristotle's apagoge and Peirce's hypothesis, we have proposed a conceptualisation of school scientific abduction with the value of offering an opportunity to investigate its basic characteristics in the settings where it occurs. Along the road, we established that some of those characteristics are relatively independent of the contexts of inference, functioning as a kind of *invariants* and allowing the use of the term "abduction" for a diversity of performances that are linked by pairs through family resemblances (as suggested by Fig. 1).

Those basic traits of abductive thinking that repeat themselves through the different contexts of occurrence and that we deem central for science education are as follows: (1) abduction produces as an outcome a new epistemic object (an "abduction-product") in a fill-up operation where radically new information, which is potentially explanatory, emerges (Blachowicz, 1998); (2) during the "abduction-process", this kind of emerged objects are tested for their robustness to explain (in a cut-down operation); and (3) abductive inference, through its marked ampliativeness, activates fruitful courses of enquiry.

In Peirce's, and also in Hanson's (1958, 1971), characterisation of abductive inference, novelty exists insofar a new "rule" is satisfactorily applied to subsume the "case". Abduction can consequently be treated as a procedure in which generated hypotheses are judged beyond their truth—in terms of their plausibility, abstraction, simplicity, coherence, generality, fruitfulness, etc. (Blachowicz, 1996). This is for us the central value of abductive inference in science education and the keystone of our didactical proposal that makes close analogies between abduction in science and that in other human activities.

In previous work (Adúriz-Bravo, 2001, 2002, 2003, 2005, 2011; Adúriz-Bravo & Izquierdo-Aymerich, 2009), one of us has suggested that abductive inference modelled with different tools contrived by Peirce can be used as a suitable model for scientific discovery or invention in the context of science education and especially in pre- and in-service science teacher education. It is our contention here that abduction—together with analogy and argumentation (Adúriz-Bravo, 2011)—is one of the "candidates for being considered general teaching strategies in science" (Clement & Núñez Oviedo, 2003: 2). While analogies and arguments have been extensively used in school science, there is still much work to be done around the implementation of abductive pieces of reasoning.

All the theoretical ideas and their corresponding implications now pave the way for the task of *identifying prospective epitomes of school scientific abduction that could have* *educational value*. Let us return to the very much cited reconstructions of how Le Verrier could have proposed his hypothesis on the existence of Neptune in the mid-nineteenth century. We can model this historical episode as the production of a Thagardian projected truth in an abduction of the existence of a new planet (Thagard, 1988: 54; Sans Pinillos, 2017: 85–88). Such an episode is too often portrayed as a scientific "discovery" in historical narratives and in textbooks, which blackbox the proposition of Neptune as a hypothesis. But the history of science tells us that Le Verrier was given the Copley medal for "proving" the existence of Neptune, and it was Galle and d'Arrest who actually *found* the planet in the skies, giving "conclusive" empirical support to Le Verrier's abduced conclusion (Grosser, 1979: 117). A richer discussion—traversed by the notion of abduction—of some of the aspects involved in a case like this one can result much more illustrating in terms of teaching the nature and use of the scientific method. A parallel case will be developed in more detail in the next, conclusive section.

4 Reflecting, and Learning How to Reflect, on Cases of Abduction in the Science Classroom

After an extensive elucidation of the concept of abduction with different theoretical tools, which aimed at finding *intelligible* and *productive* ways for teachers to introduce this concept in science education, we moved to the derivation of implications of our study for science teaching at the primary and secondary levels. At the same time, we briefly exemplified our proposal with a collection of possible epitomes of abductive reasoning in the history of science and in other contexts of human activity. In this last section, we discuss the design and application of didactical materials in which cases where abduction may be playing a key role are examined in some detail with students or teachers. Our proposal is that science teachers (learn how to) teach the explanatory nature of abduced hypotheses in relation to their capacity to generate courses of enquiry.

The sequences of presentation of abduction in the science classes of different educational levels and in pre- and in-service teacher education devised by our research group are based on an explicit argument: some historical reports presenting "discoveries" or "inventions" (written by scientists, philosophers of science, or historians of science) can be profitably reconstructed as cases of abductive thinking so as to show some key aspects of "the everyday practice of science" (Grinnell, 2019). For such a didactical reconstruction for school science, we understand the abductive process as the subsumption of a natural phenomenon, taken as the "case", under a *theoretical model*,[13] taken as the "rule" (Adúriz-Bravo, 2013a, 2013b).

We contend here that scientific investigation or enquiry, when regarded as an *evidence-based* endeavour, can be profitably connected to the use of *inferences in context* that belong with abduction in its most general sense—that of "ascent" from evidence to productive hypotheses (Adúriz-Bravo, 2001, 2002, 2004). Thus, when working with science students or teachers, we find it particularly fruitful to draw an analogy between scientific reasoning and other activities that are aimed at puzzle- or mystery-solving and make use of markedly ampliative reasoning patterns. Along this line, we have stated that applications of detective, medical, forensic, archaeological, and "gossipographic" (i.e.

[13] We take the concept of "theoretical model" from the semantic philosophy of science of the last quarter of the twentieth century (see Adúriz-Bravo, 2013a, 2019; Giere 1988, 1991).

garden-variety) thinking seem of utmost interest. In all these fields, a parsimonious collection of "facts" *selected and read* under the guidance of a strong model can be used as premises of a markedly ampliative reasoning process, which "ascends" to general, abstract, and audacious conclusions with intended explanatory power (Adúriz-Bravo, 2001, 2015, 2020).

Analogically, we consider that the solution of a problem in science usually arises from a process of modelling (Adúriz-Bravo, 2013a, 2019); our reconstruction of such process is formalised by means of an abductive reasoning pattern. In previous proposals, one of us has resorted to Peirce's famous contrastive presentation of the syllogisms of deduction, induction, and abduction in Table 1, but other Peircean formulations of the abductive process (e.g. abduction *lato sensu*, as any kind of markedly non-monotonic and ampliative inference that produces or activates hypotheses) have also shown to be educationally pertinent. Using these formalisms, our intended audiences of students or teachers are able to reconstruct various famous scientific episodes as "reverse deductive" schemas, which, as it was said, are architecturally, *but not semantically or pragmatically*, equivalent to a fallacy of affirming the consequent (Adúriz-Bravo, 2001, 2002, 2004).

In one of the designed didactical units (Adúriz-Bravo, 2005, 2013b; Adúriz-Bravo & Izquierdo-Aymerich, 2009), science students or teachers are shown how to reconstruct the "discovery" of radium by Maria Skłodowska-Curie as an abduction employing the Peircean pattern presented in Sect. 1. In such a reconstruction, the puzzling fact is the unexpectedly high and irregular radioactivity of a sample of pitchblende from the Bohemian mines of Sankt Joachimsthal (currently Jáchymov in the Czech Republic). Ideally, the result of seeing this episode as a piece of abduction would be as follows:

> The surprising fact that a fraction of a particular ore of pitchblende is more active than all its uranium content is observed by Maria.
> But if it were true that a new, extremely active radiometal exists diluted as traces in Bohemian pitchblende, this fraction of the ore being more active than all its uranium content would be a matter of course.
> Hence, there is reason to suspect that there exists a new, extremely active radiometal diluted as traces in Bohemian pitchblende is true.

The theoretical model in use by the Curies is that of *radioactivity* in metals, not yet fully developed by them and other researchers at the time of the events. The product of the model-based fill-up is a "theoretical hypothesis" (Giere, 1988) that subsumes the case under a rule pointing at radioactivity as a general *physical* phenomenon, not only associated with uranium and thorium. The abduced conclusion possesses clearly defined empirical content, which calls for further enquiry so as to confirm or disconfirm it to some extent. This is of course what happened in the decade ensuing that abduction:

> Pierre Curie and I at once carried out this research [of extraction of the new radiometal], hoping that the proportion of the new element might reach several per cent. In reality the proportion of the hypothetical element was far lower and it took several years to show unequivocally that pitchblende contains at least one highly-radioactive material which is a new element in the sense that chemistry attaches to the term. (Curie, 1966 [1911]: n/p)

In the science classrooms, our abduction-based reconstruction of how the Curies might have reasoned when "inventing" (i.e. producing the hypothesis of the existence of) radium can be profitably contrasted with various historical records; in this way, students or teachers would be performing an explicit and reflective examination of the nature of scientific methodology. We use for these purposes the lecture that Maria pronounced when accepting her second Nobel prize, accorded to her for "[t]he chemical work aimed at isolating radium in the state of the pure salt, and at characterizing it as a new element" (Curie, 1966 [1911]: n/p). Key aspects of that lecture can be interpreted as follows during the presentation of the case.

The theoretical model of radioactivity is presented by means of a law:

> I was struck by the fact that the activity of uranium and thorium compounds appears to be an atomic property of the element uranium and of the element thorium. *Chemical compounds and mixtures containing uranium and thorium are active in direct proportion to the amount of these metals contained in them.* The activity is not destroyed by either physical changes of state or chemical transformations. (Curie, 1966 [1911]: n/p; emphasis added)

A surprising fact appears when intervening on concrete radioactive materials:

> I measured the activity of a number of minerals; all of them that appear to be radioactive always contain uranium or thorium. *But an unexpected fact was noted*: certain minerals (pitchblende, chalcolite, autunite) had a greater activity than might be expected on the basis of their uranium or thorium content. Thus, certain pitchblendes containing 75% of uranium oxide are about four times as radioactive as this oxide […]. This conflicted with views which held that no mineral should be more radioactive than metallic uranium. (Curie, 1966 [1911]: n/p; emphasis added)

A hypothesis is abduced to explain that fact:

> *I then thought that* the greater activity of the natural minerals might be determined by the presence of a small quantity of a highly-radioactive material, different from uranium, thorium and the elements known at present. (Curie, 1966 [1911]: n/p; emphasis added)

And this postulation leads to a course of enquiry:

> *It also occurred to me that if this was the case* I might be able to extract this substance from the mineral by the ordinary methods of chemical analysis. (Curie, 1966 [1911]: n/p; emphasis added)

An argument in favour of the abduced hypothesis is provided, since "[i]t was vital to show that the radioactive property was connected with traces of elements that were neither bismuth nor barium" (Curie, 1966 [1911]: n/p):

> To explain this point I prepared synthetic chalcolite from pure products, and obtained crystals, whose activity was completely consistent with their uranium content […]. (Curie, 1966 [1911]: n/p)

And finally, it is clearly later on that more definite evidences in favour of the existence of radium (and hence, more robust corroboration of the abduced hypothesis) are found:

> A first *proof* that the element radium existed was furnished by spectral analysis. The spectrum of a chloride enriched by crystallization exhibited a new line which Demarçay attributed to the new element. As the activity became more concentrated, the new line increased in intensity and other lines appeared […]. (Curie, 1966 [1911]: emphasis added)

As a result of the development of this example, it is probably clear by now that the Curies' abduced hypothesis on radium was fully explanatory for a group of physicists long before there was a corpus of "validating" elements strong enough for the normative scientific standards traditionally taught. Just as this one, many historical vignettes conflict with the "received" idea of scientific method, and this is what makes for us necessary to merge some key concepts of the AKM and GW frameworks and pay more attention to the context of production of scientific explanations and argumentations.

Thus, the kind of discussion around abduction that we propose to conduct with science students or teachers is guided by a contextualised approach that recovers key elements of Peirce's pragmatic model. Our proclaimed starting point has been that the internal logic of reasoning in the context of justification of science has usually been examined from too narrow a perspective, mainly relying on the use of deductive and inductive patterns. Thus, our aim with reconstructed episodes such as the previous one is to introduce our audiences with an understanding of scientific modelling as it is conceptualised in some contemporary philosophies of science that can be characterised as semantic, representational, model-based, and cognitive (Adúriz-Bravo, 2001, 2004, 2013a, 2019). In these philosophies, *purposefully selected for their power for science education*, abduction (along with analogical reasoning) as an inferential device is deemed an irreplaceable intellectual tool for a sound understanding of how science actually works (Giere, 1991; Grinnell, 2019; Hanson, 1958; Samaja, 2005). The idea of abduction is, in our view, a substantive pillar of the nature of science that has been underexplored so far and deserves further examination from didactics of science.

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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