Article

Modeling as Scientific Reasoning—The Role of Abductive Reasoning for Modeling Competence

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Abstract: While the hypothetico-deductive approach, which includes inductive and deductive reasoning, is largely recognized in scientific reasoning, there is not much focus on abductive reasoning. Abductive reasoning describes the theory-based attempt of explaining a phenomenon by a cause. By integrating abductive reasoning into a framework for modeling competence, we strengthen the idea of modeling being a key practice of science. The framework for modeling competence theoretically describes competence levels structuring the modeling process into model construction and model application. The aim of this theoretical paper is to extend the framework for modeling competence by including abductive reasoning, with impact on the whole modeling process. Abductive reasoning can be understood as knowledge expanding in the process of model construction. In combination with deductive reasoning in model application, such inferences might enrich modeling processes. Abductive reasoning to explain a phenomenon from the best fitting guess is important for model construction and may foster the deduction of hypotheses from the model and further testing them empirically. Recent studies and examples of learners' performance in modeling processes support abductive reasoning being a part of modeling competence within scientific reasoning. The extended framework can be used for teaching and learning to foster scientific reasoning competences within modeling processes.

Keywords: scientific reasoning; abductive reasoning; models; modeling; model construction; model application; modeling competence

1. Introduction

Theoretical abduction is "the process of reasoning in which explanatory hypotheses are formed and evaluated" [1] (p. 220).

This process of reasoning addresses modeling. Hence, the concept about the phenomenon is a model [2] that develops while seeking for explanations [3]. Thus, scientific reasoning, in terms of searching for explanations to obtain insight into a phenomenon, is related to the construction of models. The derivation of hypotheses from these models and their application in empirical investigations allows the evaluation of the phenomenon [1]. As such, modeling is a prominent style of scientific reasoning that also is understood as a skill that needs to be practiced [4] and is related to competences [5] (p. 43). Thus, the framework for modeling competence was developed [6,7], respecting particularly procedural and epistemic perspectives of reasoning [8].

A model serves as a representation for communicating scientific knowledge or as a research tool for testing hypotheses about a phenomenon [9]. A model used for teaching and learning content knowledge serves as a medium for communication and meets the purpose of describing and explaining current scientific knowledge. Therefore, when using a model as medium, the focus is on model construction to represent a phenomenon accurately [7,9–11]. In contrast, a model used as a research tool is constructed for the purpose of deriving hypotheses about scientific phenomena. Hence, the focus is on model

application in research contexts to gain new insights into unknown phenomena [11]. In both communication and research contexts, model construction and model application are central parts of intertwined modeling processes: a model is constructed starting from a theoretical background and from abductive or inductive reasoning [12,13], both forms of logical inferences [14]. Deductive reasoning as the third logical inference [14] is practiced in model application, which starts with deriving hypotheses deductively from the model, usually followed by empirical testing [4].

In biology education, the framework for modeling competence (FMC) [6] has been developed and empirically validated [15,16]. The FMC structures modeling competence into aspects and levels [17] and addresses at the same time the perspectives of model construction and model application. Theoretical considerations and empirical findings [3,18] revealed the need for including another level to the FMC regarding reasoning processes in model construction with hypothesized impact for model application [7]. This extension was realized by integrating the knowledge-expanding function of explaining a phenomenon in the process of model construction, which is abductive reasoning [3,13,19]. In the initial FMC, explaining was considered as an intermediate level representing communicative functions. However, this approach did not cover the idea of developing a model by explaining a phenomenon with causes from past experiences and information [3,13,19], meaning a phenomenon is explained as best as possible through abductive reasoning [13]. Thus, the term "explanation" [3,18] describes two different practices needing to be separated: explanation in order "to make clear" for communication purposes and explanation in order "to justify" as an epistemic function. This differentiation of explaining is now integrated into the presented FMC. The process of abductive reasoning in model construction may initiate, because of its uncertainty, deductively derived hypotheses in model application and thus promote empirical investigations.

In this article, we argue that abductive and deductive reasoning are related parts within scientific reasoning regarding model construction and model application. The theoretical considerations of abductive reasoning in modeling are supported by empirical work in mathematics [20] and geography [12,21,22]. Additionally, we give some insight into learners' performance in modeling processes which support abductive reasoning being a part of modeling competence within scientific reasoning.

2. Logical Reasoning

Three forms of logical reasoning are involved in scientific reasoning and inquiry. They are summarized briefly by Peirce: "The division of all inference into Abduction, Deduction, and Induction may almost be said to be the Key of Logic" [14] (CP 2.98). In this context, abduction is about generating a cause as the best explanation for an observed phenomenon based on existing rules or theoretical knowledge ("inference to the best explanation" [23], "educated guess" [12]). This kind of reasoning is knowledge expanding, leads to creative ideas, and thus forms new theoretical inferences [24]. In contrast, inductive reasoning derives a general rule from repeated observations of a phenomenon. This inference is knowledge expanding but does not provide any principally new ideas [14]. In deductive reasoning, a general rule as theoretical basis and a cause are used to predict a result of a certain case. If the rule is true, each individual case will fit to this rule. Thus, deductive reasoning is truth preserving and logically flawless. However, as in the case of inductive reasoning, it does not generate principally "new ideas" [24]. The relationship among the three forms of logical reasoning is summarized by Peirce: "Deduction proves that something must be; Induction shows that something actually is operative; Abduction merely suggests that something may be" [14] (CP 5.171).

3. Theory of Abductive Reasoning

An established theory of abductive reasoning from cognitive psychology describes seven components of abductive reasoning [13,25]. This theory describes a continuous, implicit process with different steps that do not have to be run through in a strict order [26].

This process can lead to a consistent type of explanation free from redundancies [13]. Ideally, the process of abductive reasoning begins with the perception of a phenomenon, for which the step of *data collection* takes place in an exploratory or theory-based manner. Subsequently, these data are incorporated into an existing mental model leading to a preliminary *comprehension*. It is *checked* whether the new data contradict the previous model or remain un-understandable. These thoughts lead to the step of *resolving anomaly*. If this occurs, new *data* will be *collected*. If there are several possible explanations, alternative potentially plausible explanations will be *refined*. Due to this, it is necessary to *discriminate* by selecting one potentially plausible explanation. In the step of *checking* for consistency, both likely and unlikely explanations are included. This process of decision making may lead to the *collection* of new *data*. If *checking* for consistency is not successful, other potentially plausible explanations will be *discriminated*. Although model *testing* in the theory of Johnson and Krems is about eliminating this uncertainty about improbable explanations [13], this step can be extended to an abductively developed model. When it comes to application of this model, hypotheses are derived deductively to be *tested ("abductive model evaluation")* [1,8].

4. Models and Modeling

4.1. Concept of a Model

> "In model-based views, models are considered subsets of scientific theories–more comprehensive systems of explanations–which are created with various semiotic resources and provide semantically rich information for scientific reasoning and problem solving" [27] (p. 1110).

The term model has so many meanings that attempts merging all meanings into one definition are methodologically useless [28]. Hence, there is no unified definition of what a model in science and science education is [29,30], nor is there a unifying modeling theory [31]. Following Mittelstraß, models are replicas of a real or imaginary object with the aim of learning something about it or learning something with it [32]. This refers to both the representational function (learning something about it) of models for the purpose of communication and to the research tool function (learning something with it) to test new ideas for the purpose to generate new knowledge.

Due to the multiformity of models and since anything can become a model that is conceived of something as a model by an agent for some purpose and time [4,33–35], general properties that characterize models ontologically as special objects are absent [32,34]. Other approaches distance from an ontological perspective on models and try to conceptualize models from an epistemic point of view [30,34,36]. In this case, something becomes a model when it is used [4], developed [31], or conceived as such [34]. In his concept of model-being, Mahr suggests that an agent judges something to be a model for a specific period of time and for a specific purpose [34]. Furthermore, the distinction between the imagined mental model and the externalized model object is relevant to Mahr's conceptualization of models [26]. In this context, the model object is described as the representation of a mental model in the broadest sense, reaching from verbal analogies to graphical representations.

4.2. Concept of Model-Being

The model and the model object each stand in two relations to something: in the perspective of construction, the model stands in relation to something of which it is a model. In the perspective of application, it stands in relation to something for which it is used for as a model [9,28,34] (Figure 1). These two relationships are constitutive and inherent aspects of model-being [28,36,37].

Mahr´s concept of model-being has separated inherent properties permanently associated with the model object [34]. A model can be used by an agent as a model *of* something and *for* something in any given time.
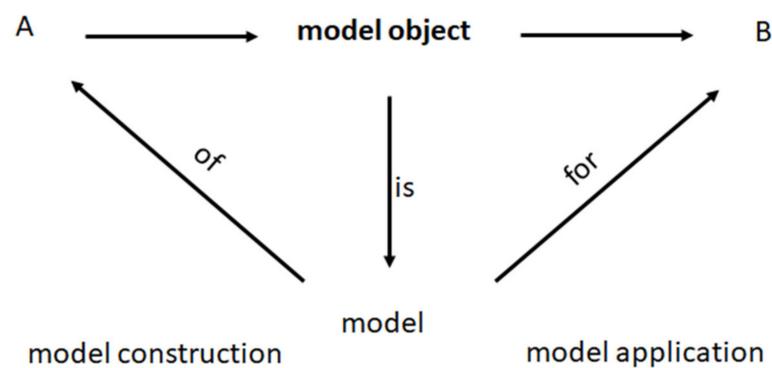
Figure 1. Mahr's concept of model-being [7] (adapted). A is a phenomenon, B is a purpose of an application.

Gouvea and Passmore also differentiated into the perspectives models *for* something (as tools for research) and models *of* something (as representation of actual knowledge) [9]. In contrast to Mahr's concept of model-being, their categorization of these perspectives are not constitutive aspects of a model in terms of a theoretical understanding of model-being. Gouvea and Passmore rather argue from a heuristic perspective to help teachers and supporting students. In accordance with this perspective, Gilbert and Justi suggest conceiving models as substitutes [38] or to describe models as epistemic tools [31] being used by agents [30].

Giere described the agent as the person making decisions about both the focus of the similarities (intent) and the goal of that focus (purpose) [36]. Mahr also consistently integrates an agent in his concept of model-being [39]. He distinguishes between the mental model, which is modeled by the agent, and the model object as the externalized representation of the agent´s mental model.

4.3. Modeling Process

The process of modeling lacks a general procedural description and definition of certain rules [40]. This is because experiences, ideas, and theories of the modeling agent influence the process and hence creative, innovative, and subjective considerations are involved [12,41]. Nevertheless, recurring elements can be identified in modeling, which ideally follow a hypothetico-deductive research logic [42,43]. In the following, the process scheme of modeling described by Krell and colleagues [15,16] stands as the basis for the integration of abductive reasoning.

In the scheme, the modeling process begins with the perception of a phenomenon, most frequently undertaken by observation (Figure 2) [44]. Observation in this case means exploring the phenomenon as a whole and without explicit assumptions [44]. These observations might lead to the formulation of hypotheses about potential relations between variables, which means that conceivable theories are generated. These hypotheses can arise through inductive reasoning from a generalized model. They are checked for consistency with other theories within model construction (Figure 2). Alternatively, abductive reasoning explains the phenomenon [13], for example with the help of analogies and is also checked for consistency (Figure 2). In case consistency is missing, the phenomenon is further explored by additional observations. If inductive or abductive inferences lead to plausible models, model construction temporarily ends. Model application begins with the deduction of hypotheses about how the model's relationships will behave under certain conditions (Figure 2). Depending on the type of hypotheses, this leads to different methodological implementations and thus into corresponding inquiry methods [6,45]. While difference hypotheses are descriptive and lead to the comparison of structures, groups, or systems, causal hypotheses are investigated through controlled experimentation and correlation hypotheses through observation (Figure 2) [44]. The analysis of data from empirical investigations lead to support or falsification of hypotheses (Figure 2). If sources

of interference in data collection are excluded as a reason for the lack of fit between the hypotheses derived from the model and the phenomenon under investigation, the model, the model object, and the concept about the modeled phenomenon have to be revised. In this process, exploration of the phenomenon restarts, which means that the process of model construction and application of a modified model begins anew (Figure 2) [4]. By initiating cognitive processes this way, models become flexible intellectual tools *for* scientific knowledge acquisition (epistemic tools) [46,47]. This function goes beyond presenting a model *of* something in a medial perspective as a means for communication.
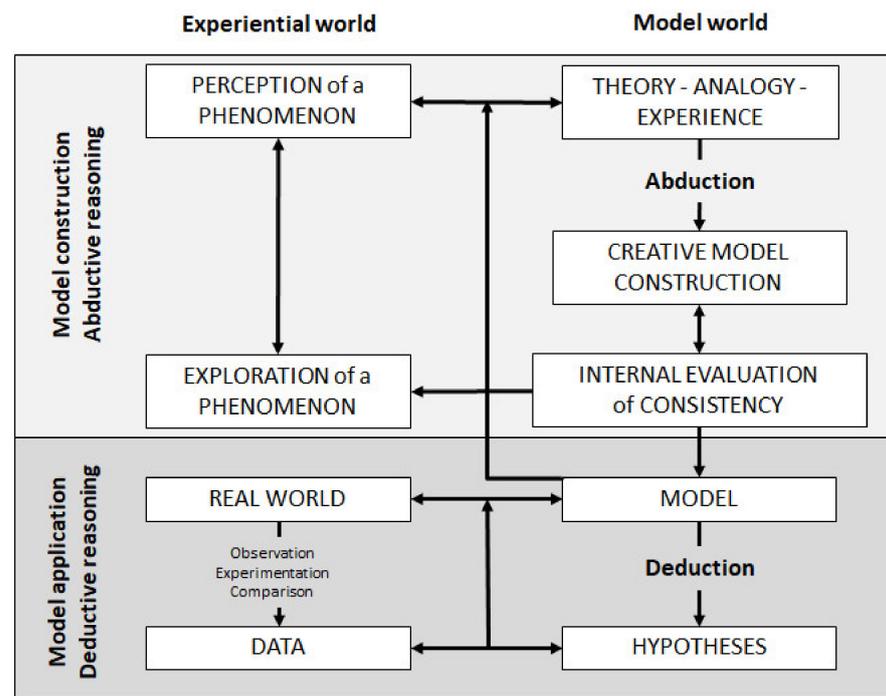

Figure 2. Abductive reasoning in model construction and deductive reasoning in model application.

5. Framework for Modeling Competence

The initial FMC [10] structures modeling competence in five aspects and three levels. The aspects were built on the basis of studies from science education research [48–50]: *nature of models, multiple models, purpose of modeling, testing models,* and *changing models* [6,10,15] (Figure 3). In the case of *nature of models,* the focus is on the similarity between the model and the phenomenon. The aspect *alternative models* addresses the question whether there can exist several models for a phenomenon. The *purpose of modeling* is guiding the modeling process for communication or as a research tool. Considering the purpose, when *testing models* and *changing models* from a medial perspective, it is about optimizing the model in context of already known details. In the research tool perspective, *testing models* and *changing models* starts from hypotheses and is led by results from corresponding empirical investigations.

The three competence levels were based on Mahr´s conceptualization of model-being and integrate perspectives on modeling focusing on the model object (level I), model construction (level II), and model application (level IIIb, Figure 3) [10]. The extended FMC integrates abductive reasoning as a further level (Figure 3, level IIIa) [7]. This new level differs from an understanding-generating explanation of common knowledge with models *of* something determining level II (Figure 3). In contrast, the knowledge-expanding function of explaining described in level IIIa is based on abductive reasoning. Abductive reasoning in model construction, like deductive reasoning in model application, involves theoretical or creative considerations. By treating level IIIa as part of level III, it is intended to clarify that model construction by abductive reasoning is scientifically demanding [13].

It may precede deductive reasoning in the sense of the hypothetico-deductive path of knowledge acquisition [43,51] (Figure 3).
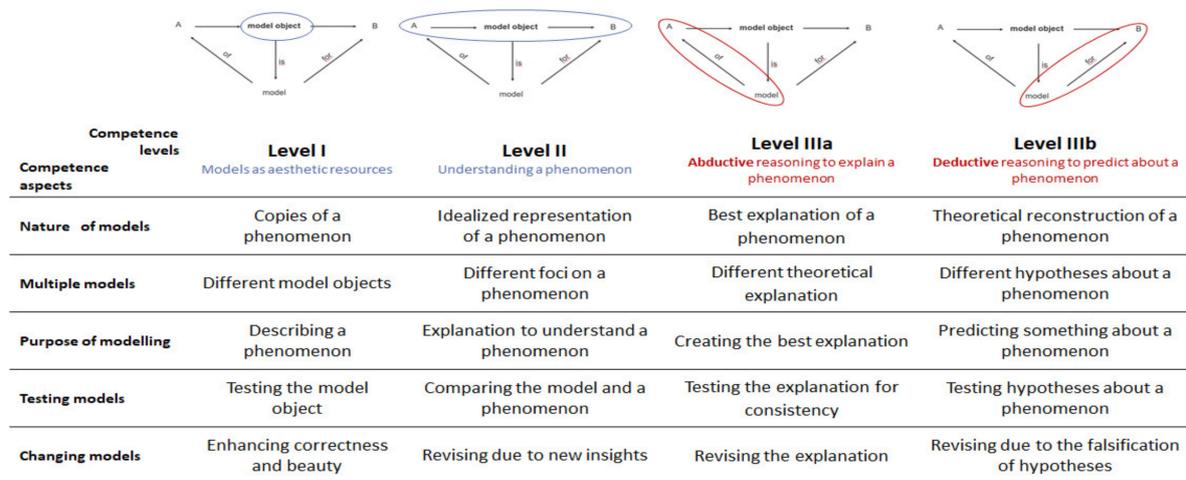

Competence levels / Competence aspects	Level I — Models as aesthetic resources	Level II — Understanding a phenomenon	Level IIIa — Abductive reasoning to explain a phenomenon	Level IIIb — Deductive reasoning to predict about a phenomenon
Nature of models	Copies of a phenomenon	Idealized representation of a phenomenon	Best explanation of a phenomenon	Theoretical reconstruction of a phenomenon
Multiple models	Different model objects	Different foci on a phenomenon	Different theoretical explanation	Different hypotheses about a phenomenon
Purpose of modelling	Describing a phenomenon	Explanation to understand a phenomenon	Creating the best explanation	Predicting something about a phenomenon
Testing models	Testing the model object	Comparing the model and a phenomenon	Testing the explanation for consistency	Testing hypotheses about a phenomenon
Changing models	Enhancing correctness and beauty	Revising due to new insights	Revising the explanation	Revising due to the falsification of hypotheses

Figure 3. Framework for modeling competence [6,7] consisting of aspects and levels.

The inclusion of a general theory of abductive reasoning in modeling [26,52], in which a model is constructed sequentially in a complex and creative process of understanding, leads to a definition of the cognitive facet of modeling competence: modeling competence comprises the abilities to initiate a theory-guided cognitive process in the creative construction of models, to gain purpose-related knowledge in the application of models, to judge about models with reference to their purpose, and to reflect on the modeling process in terms of scientific reasoning [7].

In the extended FMC (Figure 3), thinking about models and modeling that is assigned to levels I and II means to understand models and modeling as representations to achieve educational goals, which is the medial perspective [6,7,10,11]. The focus is on accuracy in model construction for communication, teaching, and learning of content knowledge. In more detail, level I deals with the ability to assess the model object from an aesthetic point of view or regarding its technical functionality without putting the phenomenon in relation to the model object, except in its capacity as a copy or for the purpose of illustration. Level II entails the ability to assess the process of model construction for understanding the represented phenomenon. The model object is a more or less accurate representation of something already known in the natural sciences.

Descriptions in level IIIa and IIIb indicate an understanding of modeling in the context of scientific investigations, which means the ability to assess models in their construction and application as research tools, which is a methodological perspective [6,7,10,11]. Level IIIa describes the ability to construct a model that provides the best plausible explanation for unknown phenomena which is free of contradictions to previous theories and explorations. Modeling is thus already a theoretical or creative process in model construction, which, associated with uncertainty, represents knowledge about a phenomenon, and can offer new possibilities for explanation. Level IIIb describes the ability to apply a model as a tool for investigating a phenomenon within scientific reasoning to empirically test its validity in the hypothetico-deductive approach; the model object as a model for something leads to processing new, thus far unexplained scientific questions.

The competence descriptions with regard to aspects and levels draw on theoretical elaborations [10,11] and, with regard to the initial FMC, extensive empirical work, which allows the use of them for assessing and promoting modeling competence for scientific reasoning [6,15,53]. However, level IIIa of the FMC with inclusion of abductive reasoning still needs to be empirically investigated.

6. State of Research

There are several approaches from different disciplines of science education connecting abductive reasoning with modeling [12,22,54]. For geoscience, Oh established a close connection between abduction and modeling (modeling-based abductive reasoning) [21,22] relating to research by Clement (addressing the solution of physical problems through abductive reasoning in modeling) [12]. Furthermore, Park and Lee point to the central role of abductive reasoning in mathematical modeling [20]. These studies rather focus on the role of abductive reasoning for constructing technically appropriate models in terms of content knowledge than on methodological (procedural and epistemic) knowledge as part of scientific reasoning competencies.

Our work aims to obtain insight into abductive reasoning within modeling processes in biological contexts. Based on Sturm [55], the reddened face phenomenon was used to obtain insight into abductive reasoning with regard to the FMC's competence descriptions [6]. Regarding this, 32 pre-service biology teachers created concept maps to solve the problem of why a fictitious person, whom they cannot talk to, has a reddened face. The participants generated abductive explanations and strategies for testing these explanations (Figure 4). A total of 159 explanations were summarized into 39 types of explanations for the reddened face. It turns out that the reddened face scenario promotes students to select different explanations by abductive reasoning. Most of the 39 given explanations were further condensed into six superior explanation types "Emotion", "Activity", "Disease", "Environment", "Blood Circulation", and "Individual Disposition" (Figure 4).

Explanation types	Single explanations	N explanations / N tested explanations
Emotion	*shame, stress, fury, anxiety, love, nervousness, excitement, anger, sadness, uncomfortable situation, emotional status, dispute, shyness, remorse, bad mood, worries*	62 / 19
Activity	*physical exertion, sport*	26 / 14
Disease	*fever, sickness, allergic reaction, intolerance, Lupus erythematodes, scarlet*	23 / 6
Environment	*temperature, sun, environmental factors, humidity*	21 / 13
Blood Circulation	*high blood circulation, high blood pressure*	11 / 1
Individual Disposition	*skin color, normal look, genetic reason, overweight*	6 / 1
Other Explanation	*alcohol, color in the face, spicy food, cosmetic treatment*	10 / 3

Figure 4. Frequencies of explanations (*N* = 159) and of tested explanations (*N* = 57) per explanation type.

In total, for 57 of 159 explanations further considerations for testing were provided. Hence, most explanations were not linked with ideas on how to test them. Explanations such as "Activity" or "Environment" have been connected to possible test strategies most frequently. In everyday life, explanations regarding "Emotion" can be tested easily through verbal communication. As this was not possible, this may explain why the participants tested explanations for "Activity" or "Environment" more frequently than for "Emotion".

The reddened face phenomenon emphasizes that a complex and creative process of abductive reasoning [13] is relevant in model construction [22] and is successful as soon as experience and analogies allow for abductive reasoning. Studies showed that for modeling the inner mechanisms in black-box scenarios [47–49], abductive reasoning

can be a successful strategy when a theoretical background is available, or creativity is involved when interpreting data. This can lead to repeated switching between abductive and deductive reasoning. If the development of explanations for the inner mechanisms of the black box is not satisfactorily [56], this is because theoretical knowledge is not available, analogies are not found, or creative solutions are lacking [57]. Unsurprisingly, because a corresponding model is missing, this leads to neither model application nor deductive reasoning [56,58].

Students' solutions for the reddened face phenomenon were structured into three different groups. In the first group, possible explanations were simply guessed without any testing strategy (*n* = 12). This result does not fit to our expectation that abductive explanations in model construction foster the switch into deductive testing in model application on its own. On the other hand, this result may be related to the fact that there were no possibilities to interact with the fictitious person nor the phenomenon itself. Thus, there was no feedback or interactive offer to test explanations. Nonetheless, most concept maps (*n* = 20) provided indicators aiming to test abducted explanations. Among these, two different strategies were identified. The first strategy in the sense of *abductive testing* (*n* = 7, Figure 5a) is characterized by the derivation of an explanation from additional speculatively observed indicators (test; cf. [13]). In contrast, the second strategy in the sense of *deductive testing* (*n* = 13, Figure 5b) is characterized by indicators for further observations being derived from a possible explanation. The strategy of abductive testing refers to the theory of abductive reasoning [13] by collecting further information beforehand within observations (Exploration of the phenomenon, Figure 2), thus in model construction. By switching to model application, applying the strategy of deductive testing of abducted explanations, students indicate strategies of deductive reasoning. This result supports the idea that abductive reasoning in model construction fosters strategies for deductive reasoning in model application.
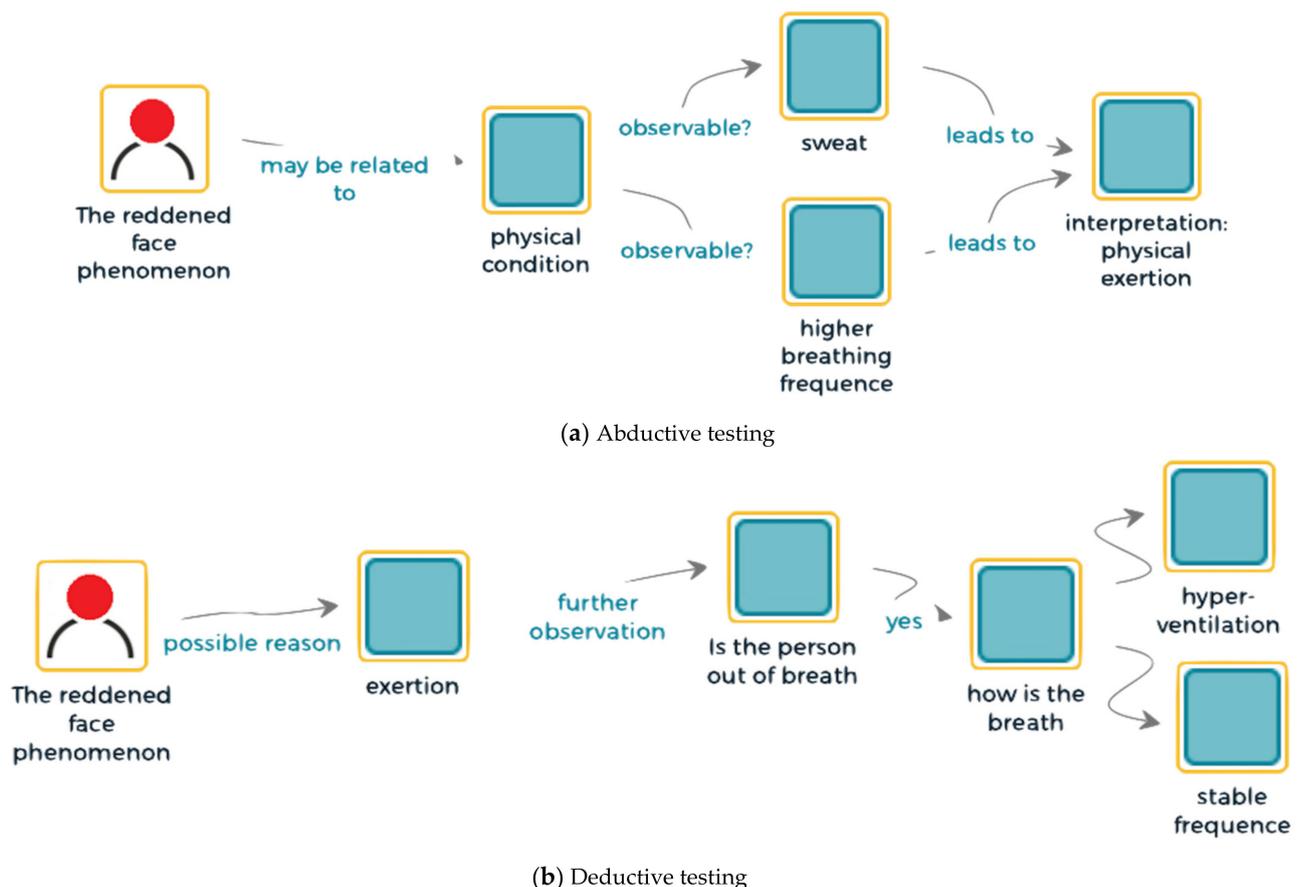

(**a**) Abductive testing

(**b**) Deductive testing

Figure 5. Excerpts of students' concept maps illustrating the strategies of abductive testing (**a**) and deductive testing (**b**).

7. Outlook

The focus on abductive reasoning within modeling processes is rather new [20,21] and led to the extension of the FMC for the field of biology in the natural sciences, thus providing a theoretical basis for the investigation of scientific reasoning in this modeling perspective. This innovation can be referred to as "abductive turn" [59], leading to broader foundations of scientific reasoning in terms of paths of knowledge acquisition in science education [6,51]. Explicating the role of induction when encountering a phenomenon, the role of abduction in model construction, and the role of deduction in model application supports Lehrer and Schauble's suggestion to consider modeling as the "signature practice of science" [60]. In this way, the prominent position of induction and deduction within the hypothetico-deductive approach might be expanded by integrating abductive reasoning in the classroom, with implications for Nature of Science perspectives [8,61]. It is necessary to further reflect on the role of abduction for gaining new knowledge and to answer the question whether abductive reasoning is underrepresented compared to induction and deduction in the hypothetico-deductive approach [62,63]. In other words, the focus on deductive inference may fall too short [64], and abduction should be implemented in school curricula as an important part of scientific reasoning.

Taking the reported rare empirical insight about the role of abductive reasoning for modeling into account, it becomes clear that scientific reasoning in modeling leads to considerations in research as well as in teaching and learning. Thus, the significance of abductive reasoning requires being investigated not only within modeling but also within the inquiry methods observation, experimentation, and comparison (Figure 2).

In teaching and learning, hypothesis-driven empirical investigations with the help of different inquiry methods are often interpreted as deductive reasoning, whereas the students are also finding causes that explain a phenomenon and therefore are reasoning abductively. This frequently remains unrecognized in schools and in teacher education at university but can be seen as a resource for promoting creative thinking within scientific reasoning which should be strengthened by further empirical evidence.

References

1. Magnani, L. Model-Based and Manipulative Abduction in Science. *Found. Sci.* **2004**, *9*, 219–247. [CrossRef]
2. Nersessian, N.J. Model-Based Reasoning in Conceptual Change. In *Model-Based Reasoning in Scientific Discovery*; Magnani, L., Nersessian, N.J., Thagard, P., Eds.; Springer: Boston, MA, USA, 1999; pp. 5–22. ISBN 978-1-4615-4813-3.
3. Rocksén, M. The Many Roles of "Explanation" in Science Education: A Case Study. *Cult. Stud. Sci. Educ.* **2016**, *11*, 837–868. [CrossRef]
4. Giere, R.; Bickle, J.; Mauldin, R. *Understanding Scientific Reasoning*; Thomson: London, UK, 2006.
5. Rychen, D.S.; Salganik, L.H. *Key Competencies for a Successful Life and Well-Functioning Society*; Hogrefe Publishing: Göttingen, Germany, 2003; ISBN 978-1-61676-272-8.
6. Upmeier zu Belzen, A.; van Driel, J.; Krüger, D. Introducing a Framework for Modeling Competence. In *Towards a Competence-Based View on Models and Modeling in Science Education*; Upmeier zu Belzen, A., Krüger, D., van Driel, J., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 3–19. ISBN 978-3-030-30255-9.
7. Krüger, D.; Upmeier zu Belzen, A. Kompetenzmodell der Modellierkompetenz—Die Rolle abduktiven Schließens beim Modellieren. *Z. Für Didakt. Naturwiss.* **2021**. [CrossRef]

8. Kind, P.; Osborne, J. Styles of Scientific Reasoning: A Cultural Rationale for Science Education? *Sci. Educ.* **2017**, *101*, 8–31. [CrossRef]

9. Gouvea, J.; Passmore, C. 'Models' of versus 'Models' for: Toward an Agent-Based Conception of Modeling in the Science Classroom. *Sci. Educ.* **2017**, *26*, 49–63. [CrossRef]

10. Upmeier zu Belzen, A.; Krüger, D. Modellkompetenz Im Biologieunterricht. *Z. Für Didakt. Naturwiss.* **2010**, *16*, 41–57.

11. Krüger, D.; Kauertz, A.; Upmeier zu Belzen, A. Modelle und das Modellieren in den Naturwissenschaften. In *Theorien in der Naturwissenschaftsdidaktischen Forschung*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 141–157. ISBN 978-3-662-56319-9.

12. Clement, J. *Creative Model Construction in Scientists and Students: The Role of Imagery, Analogy, and Mental Simulation*; Springer: Dordrecht, The Netherlands, 2008; ISBN 978-1-4020-6711-2.

13. Johnson, T.R.; Krems, J.F. Use of Current Explanations in Multicausal Abductive Reasoning. *Cogn. Sci.* **2001**, *25*, 903–939. [CrossRef]

14. Peirce, C.S. *[Harvard] Lectures on Pragmatism*; Belknap, Harvard: Cambridge, MA, USA, 1978.

15. Krell, M.; Upmeier Zu Belzen, A.; Krüger, D. Modellkompetenz im Biologieunterricht. In *Biologiedidaktische Forschung. Schwerpunkte und Forschungsgegenstände*; Sandmann, A., Schmiemann, P., Eds.; Logos: Berlin, Germany, 2016; pp. 83–102.

16. Krell, M.; Walzer, C.; Hergert, S.; Krüger, D. Development and Application of a Category System to Describe Pre-Service Science Teachers' Activities in the Process of Scientific Modelling. *Res. Sci. Educ.* **2019**, *49*, 1319–1345. [CrossRef]

17. Gogolin, S.; Krüger, D. Students' Understanding of the Nature and Purpose of Models. *J. Res. Sci. Teach.* **2018**, *55*, 1313–1338. [CrossRef]

18. Ke, L.; Schwarz, C. Using epistemic considerations in teaching: Fostering students' meaningful engagement in scientific modeling. In *Towards a Competence-Based View on Models and Modeling in Science Education*; Upmeier zu Belzen, A., Krüger, D., Driel, J., Eds.; Springer: Cham, Switzerland, 2019.

19. Kampourakis, K.; Niebert, K. Explanation in biology education. In *Teaching Biology in Schools: Global Research, Issues, and Trends*; Kampourakis, K., Reiss, M.J., Eds.; CRC Press: New York, NY, USA, 2018; pp. 237–248. ISBN 978-1-138-08798-9.

20. Park, J.H.; Lee, K.-H. How Can Mathematical Modeling Facilitate Mathematical Inquiries? Focusing on the Abductive Nature of Modeling. *Eurasia J. Math. Sci. Technol. Educ.* **2018**, *14*, em1587. [CrossRef]

21. Oh, P.S. How Can Teachers Help Students Formulate Scientific Hypotheses? Some Strategies Found in Abductive Inquiry Activities of Earth Science. *Int. J. Sci. Educ.* **2010**, *32*, 541–560. [CrossRef]

22. Oh, P.S. Features of Modeling-Based Abductive Reasoning as a Disciplinary Practice of Inquiry in Earth Science. *Sci. Educ.* **2019**, *28*, 731–757. [CrossRef]

23. Harman, G. The Inference to the Best Explanation. *Philos. Rev.* **1965**, *74*. [CrossRef]

24. Wirth, U. Die Phantasie Des Neuen Als Abduktion. *Dtsch. Vierteljahrsschr. Für Lit. Geistesgesch.* **2003**, *77*. [CrossRef]

25. Krems, J.; Johnson, T.; Kliegl, R. Kognitive Komplexität und abduktives Schließen. In *Strukturen und Prozesse Intelligenter Systeme*; Kluwe, R.H., Ed.; Deutscher Universitätsverlag: Wiesbaden, Germany, 1997.

26. Johnson, T.R.; Krems, J.; Amra, N.K. A computational model of human abductive skill and its acquisition. In *Proceedings of the Sixteenth Annual Conference of the Cognitive Science Society*; Ram, A., Eiselt, K., Eds.; Erlbaum: Hillsdale, MI, USA, 1994.

27. Oh, P.S.; Oh, S.J. What Teachers of Science Need to Know about Models: An Overview. *Int. J. Sci. Educ.* **2011**, *33*, 1109–1130. [CrossRef]

28. Mahr, B. Information Science and the Logic of Models. *Softw. Syst. Model.* **2009**, *8*, 365–383. [CrossRef]

29. Agassi, J. Why there is no theory of models. In *Theories and Models in Scientific Processes. Proceedings of AFOS '94 Workshop, August 15–26, Madralin and IUHPS '94 Conference, August 27–29, Warszawa*; Herfel, W., Krajewski, W., Niiniluoto, I., Wójcicki, R., Eds.; Rodopi: Amsterdam, The Netherlands, 1995; pp. 17–26.

30. Gilbert, J.K.; Justi, R. *Modelling-Based Teaching in Science Education*; Models and Modeling in Science Education; Springer International Publishing: Cham, Switzerland, 2016; ISBN 978-3-319-29038-6.

31. Ritchey, T. Outline for a Morphology of Modelling Methods. *Acta Morphol. Gen. AMG* **2012**, *1*, 1012.

32. Mittelstraß, J. Anmerkungen zum Modellbegriff. In *Modelle des Denkens: Streitgespräch in der Wissenschaftlichen Sitzung der Versammlung der Berlin-Brandenburgischen Akademie der Wissenschaften am 12. Dezember*; Berlin-Brandenburgische Akademie der Wissenschaften: Berlin, Germany, 2005.

33. Stachowiak, H. *Allgemeine Modelltheorie*; Springer: Wien, Austria, 1973.

34. Mahr, B. Modelle Und Ihre Befragbarkeit Grundlagen Einer Allgemeinen Modelltheorie. *Erwäg. Wissen Ethik* **2015**, *26*, 329–342.

35. Harré, R. *The Principles of Scientific Thinking*; Macmillan: London, UK, 1970.

36. Passmore, C.; Gouvea, J.S.; Giere, R. Models in Science and in Learning Science: Focusing Scientific Practice on Sense-making. In *International Handbook of Research in History, Philosophy and Science Teaching*; Matthews, M.R., Ed.; Springer Netherlands: Dordrecht, The Netherlands, 2014; pp. 1171–1202. ISBN 978-94-007-7654-8.

37. Mahr, B. Ein Modell des Modellseins. In *Modelle*; Dirks, U., Knobloch, E., Eds.; Peter Lang: Frankfurt am Main, Germany, 2008.

38. Mäki, U. Models Are Experiments, Experiments Are Models. *J. Econ. Methodol.* **2005**, *12*, 303–315. [CrossRef]

39. Mahr, B. *On the Epistemology of Models*; De Gruyter: Boston, MA, USA, 2012; pp. 301–352. ISBN 978-3-11-025357-3.

40. Morrison, M.; Morgan, M.S. Introduction. In *Models as Mediators. Perspectives on Natural and Social Science*; Morgan, M.S., Morrison, M., Eds.; Cambridge University Press: Cambridge, UK, 1999.

41. Schurz, G. Patterns of Abduction. *Synthese* **2008**, *164*, 201–234. [CrossRef]

42. Popper, K. *Logik Der Forschung*; Mohr Siebeck: Tübingen, Germany, 2005.

43. Langlet, J. Kultur der Naturwissenschaften. In *Fachdidaktik Biologie*; Gropengießer, H., Harms, U., Kattmann, U., Eds.; Aulis: Hallbergmoos, Germany, 2016.

44. Greve, W.; Wentura, D. *Wissenschaftliche Beobachtung. Eine Einführung*; Beltz: Weinheim, Germany, 1997.

45. Upmeier zu Belzen, A.; Krüger, D. Modelle Und Modellieren Im Biologieunterricht: Ein Fall Für Erkenntnisgewinnung. *Unterr. Chem.* **2019**, *171*, 38–41.

46. Bailer-Jones, D.M. Tracing the Development of Models in the Philosophy of Science. In *Model-Based Reasoning in Scientific Discovery*; Magnani, L., Nersessian, N.J., Thagard, P., Eds.; Springer: Boston, MA, USA, 1999; pp. 23–40. ISBN 978-1-4615-4813-3.

47. Knuuttila, T. Modelling and Representing: An Artefactual Approach to Model-Based Representation. *Stud. Hist. Philos. Sci. Part A* **2011**, *42*, 262–271. [CrossRef]

48. Grosslight, L.; Unger, C.; Jay, E.; Smith, C.L. Understanding Models and Their Use in Science: Conceptions of Middle and High School Students and Experts. *J. Res. Sci. Teach.* **1991**, *28*, 799–822. [CrossRef]

49. Justi, R.S.; Gilbert, J.K. Modelling, Teachers' Views on the Nature of Modelling, and Implications for the Education of Modellers. *Int. J. Sci. Educ.* **2002**, *24*, 369–387. [CrossRef]

50. Crawford, B.; Cullin, M. Dynamic Assessments of Preservice Teachers' Knowledge of Models and Modelling. In *Research and the Quality of Science Education*; Boersma, K., Goedhart, M., de Jong, O., Eijkelhof, H., Eds.; Springer: Dordrecht, The Netherlands, 2005; pp. 309–323. ISBN 978-1-4020-3673-6.

51. Priemer, B.; Eilerts, K.; Filler, A.; Pinkwart, N.; Rösken-Winter, B.; Tiemann, R.; Zu Belzen, A.U. A Framework to Foster Problem-Solving in STEM and Computing Education. *Res. Sci. Technol. Educ.* **2019**, *38*, 105–130. [CrossRef]

52. Krems, J.; Johnson, T. Integration of anomalous data in multicausal explanations. In *Proceedings of the 1995 Annual Conference of the Cognitive Science Society*; Moore, J.D., Lehman, J.F., Eds.; Erlbaum: Hillsdale, MI, USA, 1995.

53. Krüger, D.; Krell, M. Maschinelles Lernen mit Aussagen zur Modellkompetenz. *Z. Für Didakt. Naturwiss.* **2020**, *26*, 157–172. [CrossRef]

54. Clement, J.; Núñez-Oviedo, M.C. Abduction and Analogy in Scientific Model Construction. In Proceedings of the Annual Meeting of the National Association for Research in Science Teaching, Philadelphia, PA, USA, 23–26 March 2003.

55. Sturm, G. Abduktion. In *Methoden der Politikwissenschaft. Neuere Qualitative und Quantitative Analyseverfahren*; Behnke, J., Gschwend, T., Schindler, D., Schnapp, K.-U., Eds.; Nomos: Baden-Baden, Germany, 2006.

56. Göhner, M.; Krell, M. Preservice Science Teachers' Strategies in Scientific Reasoning: The Case of Modeling. *Res. Sci. Educ.* **2020**. [CrossRef]

57. Göhner, M.; Krell, M. Modellierungsprozesse von Lehramtsstudierenden Der Biologie. *Erkenn. Biol.* **2018**, *17*, 45–61.

58. Göhner, M.; Krell, M. Was ist schwierig am Modellieren? Identifikation und Beschreibung von Hindernissen in Modellierungsprozessen von Lehramtsstudierenden naturwissenschaftlicher Fächer. *Z. Für Didakt. Naturwiss.* **2021**. [CrossRef]

59. Reichertz, J. *Die Abduktion in der Qualitativen Sozialforschung: Über die Entdeckung des Neuen*; Springer: Wiesbaden, Germany, 2013; Qualitative Sozialforschung; 2., aktualisierte und erw. Aufl; ISBN 978-3-531-93163-0.

60. Lehrer, R.; Schauble, L. The development of scientific thinking. In *Handbook of Child Psychology and Developmental Science: Cognitive Processes*, 7th ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2015; Volume 2, pp. 671–714. ISBN 978-1-118-13678-2.

61. Heering, P.; Kremer, K. Nature of science. In *Theorien in der Naturwissenschaftsdidaktischen Forschung*; Krüger, D., Parchmann, I., Schecker, H., Eds.; Springer: Berlin/Heidelberg, Germany, 2018.

62. Mayer, J. Erkenntnisgewinnung als wissenschaftliches Problemlösen. In *Theorien in der Biologiedidaktischen Forschung: Ein Handbuch für Lehramtsstudenten und Doktoranden*; Krüger, D., Vogt, H., Eds.; Springer: Berlin/Heidelberg, Germany, 2007; pp. 177–186.

63. Gut-Glanzmann, C.; Mayer, J. Experimentelle Kompetenz. In *Theorien in der Naturwissenschaftsdidaktischen Forschung*; Krüger, D., Parchmann, I., Schecker, H., Eds.; Springer: Berlin/Heidelberg, Germany, 2018.

64. Evans, J.S.B. Logic and Human Reasoning: An Assessment of the Deduction Paradigm. *Psychol. Bull.* **2002**, *128*, 978–996. [CrossRef]