Chapter 9
The Black Box Approach: Analyzing Modeling Strategies

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9.1 Introduction

As outlined in Chap. 1, modeling competence in science education is understood as a multidimensional construct, comprising abilities to perform modeling practices as well as knowledge about models and the modeling process in science ("meta-modeling knowledge"). Researchers have proposed a positive relationship between these two dimensions, suggesting that "metamodeling knowledge guides the practice […], enabling students to more effectively plan and evaluate their investigations" (Schwarz et al., 2009, p. 635) and that engaging in modeling practices contributes to developing and deepening meta-modeling knowledge. There is some evidence that supports these ideas (e.g. Cheng & Lin, 2015; Gobert & Pallant, 2004; Jong, Chiu, & Chung, 2015; Schwarz & White, 2005). However, most studies have been correlational (e.g. Schwarz & White, 2005) and therefore do not allow causal inferences to be drawn. Recently published review articles (Louca & Zacharia, 2012; Nicolaou & Constantinou, 2014) have revealed that research on modeling competence tends to focus on the assessment of meta-modeling knowledge (e.g. Justi & Gilbert, 2003; Krell & Krüger, 2017; Schwarz & White, 2005). Furthermore, the quality of modeling processes has mostly been assessed post hoc by analyzing the appropriateness of modeling products (i.e. models) (e.g. Cheng & Lin, 2015; Jong et al., 2015). Consequently, Nicolaou and Constantinou (2014, p. 72); emphasized that "there is no completely coherent way to conceptualize or to assess modeling [processes]."

This contribution argues that the black box approach is suitable for conducting process-based analyses of modeling and for fostering modeling abilities when

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A. Upmeier zu Belzen et al. (eds.), *Towards a Competence-Based View on Models and Modeling in Science Education*, Models and Modeling in Science Education 12, https://doi.org/10.1007/978-3-030-30255-9_9

additional guidance and opportunities for explicit reflections are provided. In the theoretical part of this contribution (Sects. 9.2 and 9.3), the appropriateness of the black box approach for diagnosing and fostering modeling abilities is explored. In the empirical part (Sects. 9.4 and 9.5), we will illustrate how the black box approach can be used to analyze pre-service science teachers' modeling strategies and to foster secondary school students' modeling competences. Whereas study 1 contributes to science education research by providing different modeling strategies and an instrument (category system) that can be used to analyze them, study 2 offers an instructional setting that can be adapted by practitioners in science education.

9.2 Modeling

In a simplified form, scientific modeling can be regarded as an iterative, cyclical process of developing and evaluating representations of phenomena with the aim of further investigating the phenomena under consideration (Clement, 1989; Giere et al., 2006; Krell, Upmeier zu Belzen, & Krüger, 2016). Model development is understood as a creative process in which analogy generation, metaphorical reasoning, thought experiments, and imagistic simulations occur (Bailer-Jones, 1999, 2009; Clement, 2009). On the basis of the modeler's knowledge and experiences, an initial model that represents selected parts or variables of the system is developed (Clement, 1989). The model then has to be evaluated with respect to its internal consistency and the extent to which it can provide an adequate representation of what was observed (Clement, 1989; Mahr, 2011). Thus, the model itself (i.e. the model object; Mahr, 2011) has to be (logically) consistent, and the model needs to be able to reproduce or to explain the phenomenon retrospectively. From this perspective, the model can be conceptualized as a medium for adequately representing selected parts of the system (*model of something*; Gouvea & Passmore, 2017; Krell et al., 2016; Mahr, 2011; Chap. 1). Furthermore, it is possible to deduce predictions about how the system should behave under certain conditions by mentally or materially manipulating the model (Giere et al., 2006; Godfrey-Smith, 2006). These predictions can be tested by conducting experiments or by making scientific observations. If the predictions turn out to be false, it is likely that the model does not fit the system (Giere et al., 2006; Godfrey-Smith, 2006). Consequently, the model has to be changed or rejected, and the evaluation of the model starts from the beginning (cyclical process). This leads to the evaluation of assumptions and to further insights about the underlying phenomenon. From this perspective, models can be conceptualized as tools for scientific reasoning (*model for something*; Gouvea & Passmore, 2017; Krell et al., 2016; Mahr, 2011; Chap. 1).

The strategy of scientific modeling can be summarized as follows:

> *The modeler's strategy is to gain an understanding of a complex real-world system via an understanding of a simpler hypothetical system that resembles it in relevant respects* (Godfrey-Smith, 2006, p. 726).

Standard documents in science education in various countries have emphasized that scientific modeling practices should be implemented in science classes (e.g. Australia: VCAA, 2016; Germany: KMK, 2005; USA: NGSS Lead States, 2013). Campbell and colleagues proposed five “modeling pedagogies” that can be applied in science classes (e.g. Campbell, Oh, Maughn, Kiriazis, & Zuwallack, 2015): *exploratory modeling* (investigating a pre-existing model), *expressive modeling* (developing a model to express ideas about a phenomenon), *experimental modeling* (deducing predictions from a model and testing them empirically), *evaluative modeling* (comparing and evaluating alternative models of/for the same original), and *cyclic modeling* (being engaged in the cyclical process of model development, evaluation, and modification). Studies have found that expressive and exploratory modeling are the most frequently used pedagogies in science education, whereas cyclic modeling is least often applied (Campbell et al., 2015; Krell & Krüger, 2016).

9.3 Modeling and the Black Box Approach in Science Education

One approach for initiating science practices – for example, modeling – in science classes is the black box approach (e.g. Koch, Krell, & Krüger, 2015; Ruebush, Sulikowski, & North, 2009). Hereby, a black box is an entity with an invisible internal system that can be investigated by manipulating the input and observing the resulting output. A generic definition of the term black box was proposed by Glanville (1982, p. 1):

> *Briefly, a black box can be characterized as: (a) being believed to be distinct, (b) having observable (and relatable) inputs and outputs, (c) being black (that is, opaque to the observer).*

Upmeier zu Belzen (2014) highlighted that a black box may be used in science education to represent elements of science and scientific practices on three different levels. On the first level, the black box represents a natural phenomenon, and the exploration of the black box represents the process of scientific discovery. On the second level, the black box and its exploration can be seen as an abstract representative of the nature of science, and reflections on the exploration of the black box provide opportunities to reflect on the nature of science (cf. Lederman & Abd-El-Khalick, 2002). On the third level, the process of exploring the black box can be regarded as a problem-solving process that is applied not only in the sciences but also in other scientific disciplines and everyday life (Upmeier zu Belzen, 2014).

Consequently, various black boxes are used in science education for different purposes. Most published approaches for using black boxes in science education have proposed that a black box can be used as a teaching/learning aid to foster conceptual knowledge (e.g. Berge, 2007; Chakrabarti et al., 2013) or knowledge about (the nature of) science (e.g. Abd-El-Khalick, 2002; Crowe, 1968; Ferstl & Schneider, 2007; Miller, 2014). Most of these articles have been related to physics education (e.g. Berge, 2007; Chakrabarti et al., 2013; Keller & Wang, 1994; Lietz, 2007). Only a few of the studies in which a black box was used for teaching/learning provided evidence for the efficacy of the approach. For example, Akerson et al. (2000) showed that a reflective, explicit, activity-based approach that included two black box activities successfully improved pre-service teachers' views of the nature of science. Other authors were successful in fostering subjects' views of models and modeling in science by means of black box activities (e.g. Cartier, 2000; Koch et al., 2015; Ruebush et al., 2009). Furthermore, some studies have provided evidence that students positively evaluate black box activities (e.g. Hildebrandt & Oliver, 2000; Kücük et al., 2011). Finally, some authors suggest that black boxes should be used for assessment/diagnostic purposes (e.g. assessment of lateral thinking skills (Arsad et al., 2012), problem solving skills (Bünder et al., 2006; Mie & Friege, 2004), or modeling strategies (Krell, Walzer, Hergert, & Krüger, 2017)). To summarize, black box approaches are used to achieve various educational goals (e.g. fostering conceptual knowledge, knowledge about science), but empirical evidence for the efficacy of the approaches is often missing.

This article focuses on the use of a water black box (MUSE, 2002) for assessing and fostering skills related to modeling competence in science education. Hence, the black box is treated as a rather abstract representation of a natural phenomenon, and the respondents are asked to explore the black box, thereby simulating the process of scientific discovery (Upmeier zu Belzen, 2014). In study 1 (Sect. 9.4), pre-service science teachers individually engage in modeling a black box without further guidance. Their activities are videotaped and analyzed using a category system. Modeling strategies are inferred by analyzing the pattern of activities. In study 2 (Sect. 9.5), pairs of secondary school students follow an instructional sequence to model the black box in given phases and subsequently reflect on their activities. The findings propose that the sequence is appropriate for fostering students' meta-modeling knowledge and for making their modeling activities explicit.

Both studies that are introduced next use a black box that is literally a black box with a funnel on top of it so it can be filled with water. As a consequence of the arrangement of the inner system of tanks and overflow pipes (two "siphons"), and depending on the input, the output flows out through a pipe at the bottom of the box. For example, when 400 ml of water is poured into the black box six times in a row, the output pattern is 0 ml, 400 ml, 600 ml, 400 ml, 0 ml, 1000 ml (Krell et al., 2017: detailed description of the black box).

9.4 Study 1: Analyzing Pre-service Science Teachers' Modeling Strategies

9.4.1 Design, Methods

The main objectives of this ongoing study are to provide a qualitative analysis of pre-service science teachers' activities in the process of scientific modeling and to infer pre-service science teachers' modeling strategies (cf. Göhner & Krell, 2018). For this purpose, pre-service biology teachers who are enrolled in bachelors (currently $n = 1$) or masters (currently $n = 5$) programs at one public university in Germany volunteered to take part in this study. To get the participants engaged in the process of scientific modeling, the abovementioned water black box was used. Participants' task was to graphically develop a model of the inner system of the black box. Thereby, it was not necessary for participants to figure out the "correct solution" because the focus of the data analysis was on the modeling process and not on the final model.

The participants worked on this study individually. In order to get insights into their reasoning processes, they were asked to think aloud (Ericsson & Simon, 1998). The activities of the participants were audio- and videotaped, and their verbalizations were fully transcribed.

The data analysis falls within the methodological framework of a qualitative content analysis (Schreier, 2012). A deductively developed and inductively refined category system was applied to identify the participants' modeling activities. The category system included the following categories (i.e. activities): *perceiving a phenomenon*, *exploring the system*, *activating analogies and experiences*, *developing a model*, *testing the model as a model of something*, *changing the model as a model of something*, *rejecting the model*, *confirming the model as a model of something*, *testing the model as a model for something*, *refuting hypotheses*, *supporting hypotheses*, *changing the model as a model for something* (note that most categories were further subdivided into sub-categories; cf. Krell et al., 2017). Each participant's pattern of activities was analyzed and compared with theoretical descriptions of modeling processes (e.g. Campbell et al., 2015) to infer the participants' modeling strategies.

Before the participants were introduced to the black box activity, their meta-modeling knowledge was assessed using five open-ended questions (Krell & Krüger, 2016) that were developed on the basis of the framework for modeling competence. A category system (Krell & Krüger, 2016) was used to decide whether the participants expressed meta-modeling knowledge related to level I (naïve), level II (intermediate), or level III (sophisticated).

The analyses of both data sources were independently conducted by two researchers, and Cohen's Kappa was calculated as a measure of interrater agreement. Differences in the assigned categories were resolved through discussion.

9.4.2 Findings

Cohen's Kappa was 0.60 ≤ K ≤ 0.80 for the analysis of the open-ended questions, and it was 0.46 ≤ K ≤ 0.84 for the analysis of the modeling activities. In the open-ended questions, the participants mainly expressed an intermediate level of meta-modeling knowledge (level II), and only two of them expressed sophisticated views on level III.

In the following, data from one case ("Julia") are presented as an example. Julia was a pre-service biology teacher with food science as a second subject, studying in the fifth semester of a bachelors program at the time of data analysis. Julia was selected because her pattern of activities exemplifies cyclic modeling (cf. Campbell et al., 2015), which is rather seldom identified in samples of (pre-service) science teachers (see Krell et al., 2017, for a detailed description of a case of expressive modeling).

In the open-ended questions, Julia expressed meta-modeling knowledge on level II. The codeline (Fig. 9.1) illustrates the pattern of Julia's modeling activities in a chronological sequence and suggested a modeling strategy. In the codeline, each circle represents a coding unit (i.e. activity). The process analysis of Julia's modeling activities revealed that she mainly operated in six phases (Fig. 9.1): (I) an exploration phase, (II) a modeling phase (model of something), (III) a modeling phase (model for something), (IV) an exploration phase, (V) a modeling phase (model of something), and (VI) a modeling phase (model for something).

Exploration Phases (I, IV): Julia mainly explored the behavior of the black box by pouring water into the black box and observing the resulting output.

Modeling Phases (Model of Something) (II, V): Julia performed a sequential development of models on the basis of her observations (i.e. model of something).

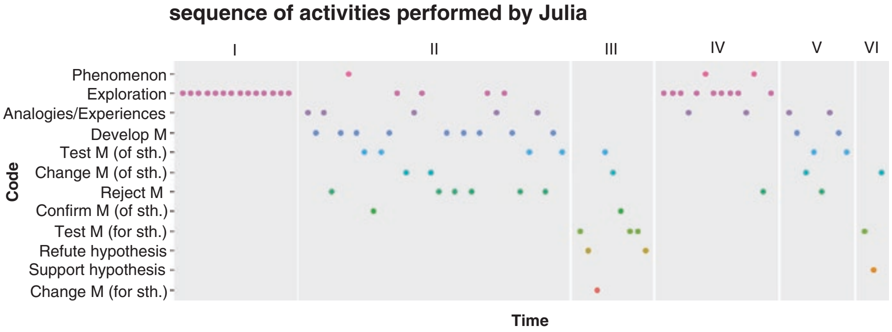

Fig. 9.1 The codeline illustrates the sequence of activities performed by Julia with time on the x axis increasing from left to right. Note that the solid circles are related to coding units (i.e. activities) and not to a standardized amount of time. See the text (paragraph 4.1) for the full names of the activities

She evaluated the models' explanatory power by retrospectively comparing her observations with the behavior she expected from the respective model. This led to the rejection of various models. During these phases, Julia activated experiences and used analogies for model development.

Modeling Phases (Model for Something) (III, VI): Julia used the models to predict the behavior of the black box and, by testing these predictions, indirectly evaluated the adequacy of the models (i.e. model for something).

The identification of the six phases in Julia's modeling process led to the interpretation of her modeling strategy as cyclic modeling (cf. Campbell et al., 2015) because she repeatedly developed, evaluated, and improved her models.

Four of the five remaining pre-service science teachers engaged in expressive modeling because they developed models of the black box on the basis of their observations but did not further evaluate their models by deducing and testing their predictions. One pre-service science teacher demonstrated a rather unsystematic method of model development because, for example, he did not consequently develop his models on the basis of the observations he made, but he instead used models to express his ideas without evaluating the ideas with respect to the data.

Julia expressed meta-modeling knowledge that would fall on level II, which means an understanding of models as models of something, but she showed a cyclical modeling strategy and used her models as models for something (Chap. 1). As in Julia's case, there was no coherent relationship between meta-modeling knowledge and modeling strategies for two other participants: They expressed an understanding on level III but did not perform cyclic modeling (but instead engaged in expressive and unsystematic modeling). The other three participants consistently expressed an understanding that fell on level II and engaged in expressive modeling.

9.4.3 Conclusion

In science education research, a positive relationship between meta-modeling knowledge and modeling processes is assumed (e.g. Schwarz et al., 2009; Schwarz & White, 2005). However, most related studies have been correlational and thus did not allow inferences to be made about causal relationships. Furthermore, modeling processes are often assessed post hoc by analyzing modeling products (e.g. Cheng & Lin, 2015; Jong et al., 2015). Consequently, researchers have emphasized that there is no coherent way to assess modeling processes (Nicolaou & Constantinou, 2014; Chap. 3) and that "one of the most pressing needs for future research is to study the relationship between […] explicit knowledge concerning the nature of science and the process of modeling, with the ways in which students engage in model creation and revision" (Louca & Zacharia, 2012, p. 486). This study contributes to filling in these gaps in science education research by providing a category system that can be used to analyze individual pre-service science teachers' modeling strategies (Krell et al., 2017). Furthermore, the findings so far – based on a rather small sample of six pre-service biology teachers – suggest that there is not necessarily a coherent relationship between pre-service science teachers' meta-modeling knowledge and their modeling strategies. This calls into question the assumption that is quite popular in science education research that meta-modeling knowledge guides modeling practices (e.g. Schwarz et al., 2009).

9.5 Study 2: Fostering Students' Understanding of Models and Modeling

9.5.1 Design, Methods

The purpose of this study was to explore the effectiveness of an intervention concerning secondary school students' (grades 10, 11) meta-modeling knowledge (Koch et al., 2015). The intervention consisted of three parts: (1) a black box activity that provided a modeling task, (2) reflective classroom discussions about models and modeling, and (3) application tasks with biological contexts. We used a quasi-experimental design with an experimental group ($n = 89$) and a comparison group ($n = 84$) involving a pre-test and a post-test. The comparison group only participated in the pre- and post-tests. Between the two testing occasions, they took part in regular biology classes with no focus on models or meta-modeling knowledge.

9.5.1.1 Black Box Activity

The aim of the first part was to enable the students to participate in a modeling situation. The black box was the water black box described above, which was programmed as an interactive computer experiment (https://tetfolio.fu-berlin.de/web/440484). The students used tablets to examine the black box. The activity was structured around different modeling tasks that referred to the development and evaluation of models: (1) Pour 400 ml of water into the black box. (2) Draw a model of the inner mechanism of the black box. (3) Deduce a prediction about what could happen if you pour another 400 ml of water into the black box again. The purpose of this procedure was to get the participants to run through a cyclical modeling process. The participants worked in pairs in order to support communication and to offer mutual support.

9.5.1.2 Reflective Classroom Discussions

During the second part of the intervention, the students reflected on their activities. To initiate the reflection process, the students were asked to visualize the modeling process. For this purpose, the students were asked to show how predefined and

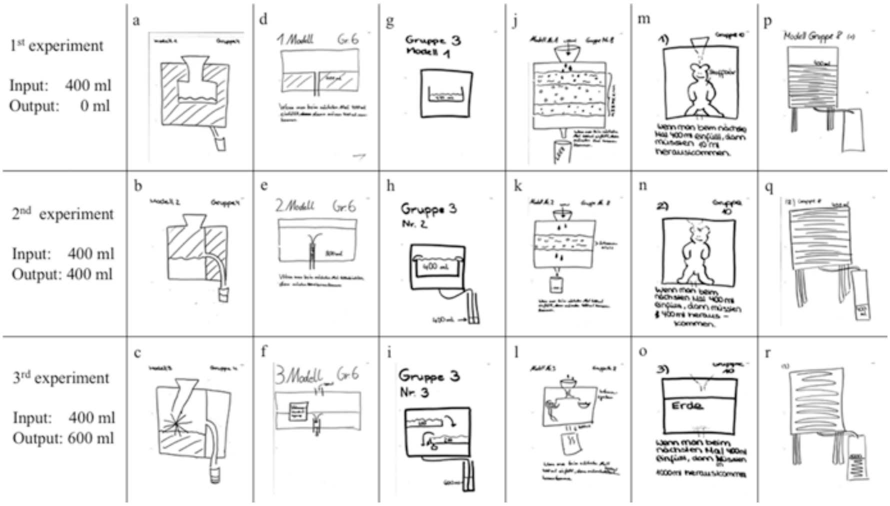

Fig. 9.2 (**a**–**r**) A selection of the students' models of the black box (Meaning of texts in the pictures: "If we pour 400 ml in, 400 ml (**d**, **e**, **k**, **l**, **n**)/0 ml (**j**) / 10 ml (**m**) /1000 ml (**o**) should pour out")

self-selected terms (e.g. "black box," "model 1," "model 2," "prediction 1," "prediction 2") were related to each other in a process diagram. While they were reflecting on their models, the students also presented and compared their models (Fig. 9.2). Additionally, they were asked questions that referred to the different aspects of modeling competence, for example, concerning the relationship between the black box (as an original) and the drawing of the black box (as the related model) or concerning the role of deduced predictions.

9.5.1.3 Application Tasks

The students were prompted to apply their generic meta-modeling knowledge to different biological contexts by relating the process diagrams to different biological examples (e.g. modeling DNA; cf. Giere et al., 2006).

Paper-pencil tests with the five open-ended questions described above (Sect. 9.4.1; cf. Krell & Krüger, 2016) were used to assess the students' meta-modeling knowledge. The data were analyzed as described (Sect. 9.4.1), which means that a category system (Krell & Krüger, 2016) was used by two researchers independently to decide whether the participants expressed meta-modeling knowledge related to level I (naïve), level II (intermediate), or level III (sophisticated). Cohen's Kappa was calculated as a measure of interrater agreement, and differences in the assigned categories were resolved through discussion.

In the following section, the results of the pre- and post-tests are provided to argue for the efficacy of the intervention in fostering students' meta-modeling knowledge. In addition, we present some of the models that were developed by the students.

9.5.2 Findings

The students developed different models of the black box. Fig. 9.2 shows examples of the students' drawings in order to illustrate the diversity of the models that were developed. The progression of each model during the black box activity is arranged in a column. Different models in a row allow for the comparison of different ideas on the basis of the same empirical data (i.e. in the same phase of the black box activity).

Some students (e.g. pictures p-r) drew only observable aspects and neglected the tasks that required them to develop a model of the presumed inner mechanism. Other groups (e.g. pictures c, f, i) considered the hypothetical structure of the black box but did not evaluate the internal consistency. It can be seen that the assumed mechanisms could not explain the observed data, especially when the output changed in different ways even when the input was the same.

Some of the students added a prediction to their drawing (e.g. picture d: "If we pour 400 ml in, 400 ml should pour out"; j: "If we pour 400 ml in, 0 ml should pour out"). Some of these predictions were based on the model as students were asked to do, but some were just guesses. Even though the task was to formulate a prediction, not all students did so.

Cohen's Kappa for the analysis of the open-ended questions was K = 0.65. In the experimental group, there was a significant shift in understanding in the aspects of the nature of models ($p < 0.001$, $r = 0.451$), purpose of models ($p < 0.001$, $r = 0.429$), testing models ($p < 0.001$, $r = 0.510$), and changing models ($p < 0.001$, $r = 0.412$), with mostly medium-sized effects. For the aspect of the nature of models, there were no students who expressed a sophisticated view (level III) on the pre-test, which changed to 37% on the post-test (purpose of models: from 3% to 22%; testing models: from 2% to 29%; changing models: from 0% to 13%).

Positive significant differences can also be observed in the comparison group regarding the aspects of multiple models ($p = 0.016$, $r = 0.287$) and changing models ($p = 0.021$, $r = 0.272$; small effect sizes). These differences reflected small shifts ranging from 20% to 21% (multiple models) or from 0% to 1% (changing models) of the students with a sophisticated meta-knowledge of modeling (level III).

9.5.3 Conclusion

On the pre-test, the participants primarily expressed naïve or intermediate views (levels I, II). This is in line with findings from other studies (e. g. Grünkorn, 2014). The occurrence of sophisticated views on the post-test indicated the efficacy of the intervention. Based on similar studies (e.g. Akerson et al., 2000; Krell, Koska, Penning, & Krüger, 2015), it can be argued that the combination of engaging in scientific practices and explicit reflections caused the positive shift in students' meta-modeling knowledge.

It can be further argued that a structured learning environment enables students to engage in the process of model development. On the basis of the available data and students' personal experiences, they developed models of the (assumed) inner mechanism of the black box. The formulation of a model-based prediction was intended to support the application of the models as *models for something* (Gouvea & Passmore, 2017). The absence of model-based predictions in some groups pointed toward difficulties for students with the cyclical process of modeling and emphasized that often guidance or scaffolding by teachers is necessary for students to run through this process (Louca & Zacharia, 2015).

9.6 Summary and Overall Conclusion

To summarize, the studies discussed in this article highlight the idea that black box activities can be used to facilitate modeling practices (Göhner & Krell, 2018). More precisely, this article contributes to science education research by providing qualitative, process-based analyses of individual modeling processes (Louca & Zacharia, 2012; Nicolaou & Constantinou, 2014; Chap. 3) and by providing empirical evidence for the efficacy of the black box approach to foster modeling competence in science education.

The category system, which was used to analyze the pre-service teachers' modeling activities is available (Krell et al., 2017) and provides a tool for process-based analyses that can be used by science education researchers. Practitioners in science education can use the black box intervention (available online, see above) in their classes to get their students engaged in modeling processes.

As emphasized above, black box approaches are widely used in science education research to reach various educational goals (e.g. fostering conceptual knowledge, knowledge about science), but empirical evidence for the efficacy of the approaches has been missing. From this point of view, this article provides evidence for the educational power of black box activities for facilitating and fostering scientific practices (Upmeier zu Belzen, 2014).

This chapter is based in part on work supported by the German Research Foundation under project number 327507949. Any opinions, findings, and conclusions or recommendations expressed in this chapter are those of the authors and do not necessarily reflect the views of the DFG.

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