Phenomenon-based learning and model-based teaching: Do they match?

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Abstract. The goal of physics teaching is to guide students from their everyday conceptions and activities to scientific models and practices. In essence, there are two different ways toward that goal: Phenomenon-based instruction and model-based instruction. Phenomenon-based instruction has been characterised by subjectivity, affectivity, mediation, exploration, and restrained model use. By definition, model-based instruction must be described by diametrically opposed characteristics: objectivity, rationality, confrontation, hypothesis testing, and extensive model use. Thus, the physics teacher may think that the two methods of teaching and learning do not match. However, we will see that both methods can be combined to guide students stepwise from phenomena to models.

1. Introduction
Physics involves a continual transition between the world of phenomena and the world of models. In the physics classroom, students need to have an opportunity to experience this interplay themselves. According to science education standards in various countries, students should be able to explore phenomena and to apply models [1-3]. However, the standards do not imply a specific teaching method. Thus, it is up to the teacher to decide how to fulfill the standards. Broadly speaking, the physics teacher may choose between phenomenon-based physics instruction [4-13] and model-based physics instruction [14-35]. By definition, phenomenon-based instruction is the opposite of model-based instruction: Experts have defined concrete, normative, and testable criteria for phenomenon-based instruction [4,5].

![Fig. 1. Criteria for phenomenon-based [4] instruction.](image)

Thus, teachers may think that model-based physics instruction is incompatible with phenomenon-based physics instruction. We will see that this is not true.

First, we will review the criteria for phenomenon-based instruction [4,5] (Section 2). Then, we will infer an opposite set of criteria for model-based instruction (Section 3). Afterwards, we will see how teachers can fulfill both sets of criteria (Section 4), making physics instruction phenomenon-based and model-oriented (Section 5).
2. Criteria for phenomenon-based instruction

There are five expert-based criteria for phenomenon-based instruction: (1) Subjectivity, (2) affectivity, (3) mediation, (4) exploration, and (5) restrained model use [4]; see Figure 1, and the left-hand column of Table 1.

2.1. Subjectivity

Subjectivity means that students gain scientific insights through personal experience. The teacher uses the students’ everyday experience as a starting point for instruction. In class, the teacher encourages ‘subjective’ (‘immersive’) experiments, where students are part of the setup. Thus, the students experience the phenomenon as an interplay between the perceiving subject and the perceived object. In exploring the phenomenon, the students rely on their own senses. The students’ observations are qualitative. To describe how their own actions affect the appearance of the phenomenon, the students use conditional phrases, such as: ‘If I [do a certain thing], then I observe [a certain effect]’. The teacher expects students to find structural relationships (qualitative patterns) among observable facts.

2.2. Affectivity

Affectivity means that the teacher turns physics into an emotional experience. The teacher makes an everyday phenomenon interesting by isolating or modifying some aspect of it. In presenting the phenomenon, the science teacher acts similar to an artist: With big, simple, and dynamic presentations of the phenomenon, the teacher invites students to become perceptually and emotionally immersed. Such an “aesthetic experience is a precognitive, sensuous experience” [10]. The teacher encourages students to be emotionally involved in the phenomenon and to express their feelings. The teacher also accepts students’ negative feelings. Thus, the teacher promotes not only student interest and motivation, but also emotional and social competences.

2.3. Mediation

Mediation happens when the teacher closes the gap between the students’ everyday world and the world of physics. The teacher uses everyday phenomena as a foundation for students’ scientific insights. The teacher plans to increase the students’ understanding step by step. To guide students from cursory perceptions to physical conceptions, the teacher asks students to observe intently. To fill the gap between everyday activities and scientific practices, the teacher offers exploratory experiments (‘nature games’), which range from playful to systematic [6]. To mediate between students’ and scientists’ ideas, the teacher builds on students’ correct ideas. In classroom discussions, the teacher uses the method of the Socratic dialogue [12]. To translate from everyday language to scientific language, teacher and students improvise an intermediate ‘classroom language’. The students’ scientific insights are grounded in personal experience, so they are applicable in everyday situations.

2.4. Exploration

Exploration is a mode of experimentation in which students can familiarize themselves with the phenomenon. For exploration, hands-on experiments are more suitable than demonstration experiments. The design of an exploratory experiment is lifeworld-oriented: it is inspired by a situation in which the phenomenon occurs naturally. In such an experiment, students observe how the phenomenon changes as they change the setup. By varying many parameters, students find the necessary conditions for the phenomenon. Based on these necessary conditions, the class may develop a logical series of simple experiments for a systematic transition between various forms of the phenomenon [13]. To describe which experimental actions produce which results, students use conditional phrases. Inductive reasoning leads from specific observations to empirical laws. Students formulate these laws like this: ‘[Under certain conditions], [a certain effect] occurs’. Such generalized descriptions of comprehensive observations are the basis for predictions.
2.5. Restrained model use
In phenomenon-based instruction, the teacher asks students to describe, explain, and predict a phenomenon in terms of its conditions of appearance only. Models are avoided as far as possible. If a model is ever used, it only serves to describe observable facts or a mathematical analogy. The teacher ensures that this single model accounts for numerous phenomena.

3. Criteria for model-based instruction
By definition, model-based instruction is the opposite of phenomenon-based instruction, so we will characterize it by opposite criteria. The opposites of subjectivity, affectivity, mediation, exploration, and restrained model use are (1) objectivity, (2) rationality, (3) confrontation, (4) hypothesis testing, and (5) extensive model use; see Figure 2, and the right-hand column of Table 1.

![Fig. 2. Criteria for model-based instruction.](image)

3.1. Objectivity
The teacher emphasizes that physical objects are independent of perception [4,14,15]. Accordingly, the class uses ‘objective’ (‘detached’) experiments, where the setup is separate from the observer [4]. Observations are made multiple times by multiple people [36]. Moreover, the teacher stresses that sense perception is limited and fallible, calling for adequate and accurate methods of measurement [4]. Physical quantities are measured with calibrated devices. The goal is to find a functional relationship between quantitative data [13].

3.2. Rationality
In model-based instruction, students get to know physics as a cognitive exercise within a logical framework. All phases of model-based inquiry require reasonable choices: Students need to decide what kinds of data to collect, how to measure variables, how to collect data, which variables to control, how to analyze the data, how to represent the data, and how to deal with unexpected data [17]. The teacher asks students to think critically about interpretations of experimental results, and about the validity of model-based claims. Students need to convince the class that their models are logically coherent and consistent with experience [17]. Model-based instruction promotes the students’ thinking skills [19].

3.3. Confrontation
The teacher challenges students’ incorrect ideas. Presenting a phenomenon that the students cannot explain, the teacher throws them into a crisis of understanding: The students “are confronted with a new pattern that cannot be represented by any model already developed” [16]. Thus, unexpected phenomena serve as a motivation for modeling. During model creation and revision, students are confronted with different ideas by their peers. If students fail to develop an appropriate model, the teacher presents the target model [16].
Table 1. Overview of opposite criteria, with sub-criteria and examples

| Subjectivity | Model-based instruction |
|--------------|-------------------------|
| Objectivity  |                         |
| Emotivity    |                         |
| Affectivity  |                         |
| Mediation    |                         |
| Exploration  |                         |
| Restrained modeling |                     |

Subjectivity

Object is independent
- e.g., “The light distribution exists without a viewer”

Measuring devices
- e.g., digital camera

Quantitative
- e.g., “The focal length is 25 mm”

Functional relationships
- e.g., \( \frac{1}{f} = \frac{1}{o} + \frac{1}{i} \)

Rationality

Logical framework
- e.g., the structure of Newton’s Opticks [41]

Critical thinking
- e.g., evaluating Newton’s experimentum crucis [42]

Persuasive arguments
- e.g., Newton’s proof of diverse refrangibility [41]

Cognitive skills
- e.g., testing hypotheses [41]

Confrontation

Unexpected phenomena
- e.g., if a lens is partly covered, the projected image stays intact [43]

Crisis of understanding
- e.g., discrepancy between view through a lens and projection with a lens: “We were confused!” [44]

Model revision
- e.g., ‘holistic’ → ‘point-to-point’ scheme [43]

Challenging students’ incorrect ideas
- e.g., have students look from the lens image back through the lens to counter the misconception that the whole object might thus be seen [37]

Hypothesis testing

Theory-laden experiments
- e.g., laser beam through a semi-circular glass block

Select parameters
- e.g., angle of incidence

Deductive reasoning
- e.g., deriving the law of refraction from Huygens’ principle

Developing appropriate models
- e.g., devising a wave model to explain refraction

Extensive modeling

Unobservable causes
- e.g., oscillating electromagnetic fields

Modeling is crucial
- e.g., wave model for constructive interference

Multiple models
- e.g., ray vs. wave vs. photon

Subject and object are interdependent
- e.g., ‘Without a viewer, there would be no image’

Senses
- e.g., eyesight

Qualitative
- e.g., ‘If the foreground appears sharp, the background appears blurry’ [37]

Structural relationships
- e.g., ‘A blurry lens image corresponds to a superposition of sharp images from diverse lens-points’ [37]

Emotional experience
- e.g., the marvelous sight of a rainbow

Aesthetic perception
- e.g., looking at spectra from an artistic viewpoint

Impressive phenomena
- e.g., large, free-floating spectral images

Social skills
- e.g., listening to each other

Known phenomena
- e.g., foreground and background objects cannot be seen sharp at the same time [37,38]

Increase in understanding
- e.g., analogy between the eye and a camera [38]

Experimental variation
- e.g., eye → eye model → lens experiment [38]

Building on students’ correct ideas
- e.g., analyze the views and images from individual lens-points to build on the idea that a whole image goes from the object through the lens [38]

Lifeworld-oriented experiments
- e.g., looking down into a water basin [39]

Multiple parameters
- e.g., head position, one/two eyes, eyeline orientation [39]

Inductive reasoning
- e.g., arriving at the law of refraction by comparing apparent depth with real depth [39]

Getting familiar with phenomena
- e.g., seeing how transparent media seemingly lift objects toward the viewer [39]

Descriptive
- e.g., ray model for angles of diffraction orders

Modeling is optional

Single model
- e.g., light path [40]
3.4. Hypothesis testing
In model-based instruction, a heavily theory-laden experiment serves to test model-based hypotheses. To arrive at a hypothesis, students use deductive reasoning: Based on a general model, students infer specific instances of a phenomenon. They state their hypotheses like this: ‘Due to [certain hypothetical causes], [a certain effect] will occur [under certain conditions]’, cf. [17]. In the experiment, only few parameters are varied, namely those specified by the hypothesis.

3.5. Extensive model use
In model-based instruction, modeling is crucial. Students use multiple models to account for a given phenomenon: During model development, students try various versions of their initial model; during model application, students represent different aspects of a phenomenon with different models, cf. [29]. In particular, students may use descriptive as well as explanatory models. Still, the teacher prefers explanatory models, which typically refer to unobservable causes [17].

4. Compatibility of phenomenon-based and model-based instruction
4.1. Complementarity
Let us look at the opposite sets of criteria in Table 1. Clearly, a teacher cannot fulfill them at the same time: Objectivity counters subjectivity, rationality precludes affectivity, confrontation disturbs mediation, hypothesis testing excludes exploration, and restraint forbids extensive modeling. The two sets of criteria are contradictory.

Still, established methods of phenomenon-based [8] and model-based [16] instruction have the same overall structure: First, phenomenon exploration; then, model use. Thus, some aspects of phenomenon-based instruction are already part of model-based instructional designs, and vice versa. Although the criteria for phenomenon-based and model-based instruction cannot be fulfilled at the same time, the teacher may transition between the characteristics over time (Fig. 3).

4.1.1. Subjectivity before objectivity. Objectivity is a standard for science; an ideal that can only be approached by reducing subjectivity [36]. According to an empirical study [36], objectivity arises in the physics classroom through social interaction, increased respect (toward materials, peers, and ideas), and through a transition

- from touching objects to removing oneself,
- from a holistic experience to an analytic perspective,
- from personal ideas to detached observations,
- from everyday language to science language [36].

Accordingly, the teacher can guide students from subjectivity toward objectivity: First, they do subjective, immersive experiments; then, they do objective, detached experiments. First, they use qualitative observation in everyday situations and exploratory experiments to find structural relationships; then, they can use quantitative experiments to find functional relationships. Mathematical modeling [30] enables objectivity: “For objective […] knowledge of the universe, […] one needs to superpose the rational world of mathematics on the empirical world” [16].

4.1.2. Affectivity before rationality. Pure affectivity and pure rationality are humanly impossible because feeling and thinking interact. Rationality can only be approached by reducing affectivity. Thus, students can go from affectivity toward rationality: When they observe an impressive phenomenon, they may share their feelings, but to find structural or functional relationships, they need to share their thoughts. During phenomenon-based and model-oriented inquiry, strong emotions like joy or frustration yield to subtle emotions like respect or content, while actions and ideas become more systematic.
4.1.3. **Mediation through confrontation.** No mediation without confrontation. Even if the teacher tries to close the gap between everyday experience and scientific practice by providing exploratory experiments [6], students will be confronted with unexpected aspects of the phenomenon [37]. In addition, students will be confronted with the subjective, diverse interpretations by their peers.

Conversely, even if the teacher uses the strategy of cognitive conflict, it is the teacher’s job to mediate between students’ and scientists’ ideas: “The teacher would […] bring concerned students first to a conscious state of *cognitive disequilibrium*, and direct them afterwards to negotiate things […] by invoking Socratic dialogues” [16]. To correct students’ misconceptions, the teacher may build on their correct ideas [37].

4.1.4. **Exploration before hypothesis testing.** Without a model, hypothesis testing is impossible [17]. Without exploration, it is hard for students to create a model. Thus, exploration comes before hypothesis testing: First, students do exploratory experiments, varying multiple parameters, describing the phenomenon and its conditions of appearance, and inducing empirical laws. Then, they can predict effects for specific parameters.

In phenomenon-based language, predictions and explanations have essentially the same structure as descriptions, always referring to the conditions for the phenomenon, *cf.* [34]:

\[
\text{[Once/because/when certain conditions are given],}
\]
\[
\text{[a certain phenomenon] will appear/has appeared/is appearing.}
\]

In model-based language, however, explanations and predictions require a causal phrase, expressing a mechanism underlying the phenomenon, *cf.* [17]:

![Figure 3. From phenomenon-based to model-based instruction.](image-url)
[Once/because certain conditions are given],
[a certain phenomenon] will appear/has appeared,
\textit{due to [certain causes]}. 

Thus, phenomenon-based claims can be transformed into model-based claims by adding a phrase referring to a cause: First, students predict and explain effects in terms of given conditions only; later, they use a model to support these predictions and explanations.

4.1.5. \textit{Restrained model use before extensive model use}. In physics instruction, it is possible to transition from restrained to extensive model use: First, the students focus on observable conditions for the phenomenon; later, they may imagine causes underlying the phenomenon. Correspondingly, the students proceed to higher levels of model use: First, they use descriptive models, later, they may use explanatory models.

If they revise models themselves, and if they use different models for different aspects of a phenomenon, students learn that models are interpretations that are neither true nor false, but only more or less useful for describing, predicting, and explaining phenomena.

4.2. \textit{Possible complications during the transition}

A transition from phenomenon-based to model-based characteristics is logically possible. However, complications may arise because the opposite sets of criteria are based on (1) different attitudes toward models, (2) different preferences for conceptual change strategies, and (3) different attitudes toward phenomena. Let us look at these differences and find a balance so that the transition may succeed.

4.2.1. \textit{Different attitudes toward models}. Phenomenon-based and model-based instructors differ in their attitude toward descriptive versus explanatory models.

Phenomenon-based teachers \textit{avoid explanatory models} to avoid the risk of mistaking imagination for reality [4,10]. Moreover, phenomenon-based teachers believe that one can understand a phenomenon without imagining underlying causes. Understanding means, primarily, discovering similarities between the various forms of a phenomenon [4,10]. An explanatory model is a shortcut between theory and a specific form of the phenomenon; yet risky.

Whereas phenomenon-based teachers are content with descriptive models, model-based teachers are not: “The goal of science is to provide causal accounts of events and processes, as opposed to accumulating descriptive detail about phenomena or merely seeking patterns” [17]. Model-based instructors believe that “authentic inquiry […] is directed at the development of theoretical mechanisms with entities that are not directly observable, such as […] magnetic fields, and polarized hydrogen atoms” [23]. Model-based teachers \textit{aim for explanatory models} because these account for diverse and complex phenomena [17].

Physics \textit{without} explanatory models may be unsatisfying for students. Physics \textit{with} explanatory models may be misleading for students. \textit{If teachers emphasize the hypothetical character of explanatory models, they may encourage explanatory modeling (in addition to descriptive modeling).}

4.2.2. \textit{Different preferences for conceptual change strategies}. Phenomenon-based instructors usually choose a different strategy for conceptual change than model-based instructors.

Phenomenon-based instructors try to guide students along a “\textit{continuous (evolutionary)}” [45] \textit{learning path}. They promote conceptual change by building on students’ everyday experience and students’ correct ideas. Many are inspired by Martin Wagenschein. His phenomenon-based teaching method is ‘\textit{genetic}’ (so students can follow how scientific knowledge is generated), ‘\textit{Socratic}’ (with dialogue leading from personal accounts to scientific accounts), and ‘\textit{exemplary}’ (with students exploring a personally relevant case to get to scientific principles) [12]. Along these lines, Østergaard proposes a teaching design for “introducing scientific concepts […] as a continuation of, and \textit{not} as a contradiction to, the students’ everyday concepts” [8]. Phenomenon-based teachers try to make the
students’ path to scientific ideas as smooth as possible [6] by fulfilling three conditions of conceptual change: Scientific ideas must appear intelligible, plausible, and fruitful [46].

Model-based teachers focus on a different condition for conceptual change: Students must get frustrated [46] with their initial conception: “A new model is introduced […] only after students realize the limitations of a previous model” [16]. Conceptual change is started here by a cognitive conflict that motivates for model revision [31]. “The teacher first helps students realize that they cannot treat the empirical situations at hand with the knowledge they already possess, and that they need to develop a new model” [16]. Model-based teachers believe that “periods where little progress is made are frustrating […] but they […] provide necessary preparation for the later insight” [24]. Thus, model-based teachers take their students on a “discontinuous (‘revolutionary’)” [45] learning path.

Still, some model-based teachers make the learning path smoother by using intermediate models [33,35] as “stepping-stones” [28], and by using Socratic dialogue [16,27]. Conversely, phenomenon-based teachers must accept that learning paths are rarely as smooth as planned [37]. Real learning paths will not be ideally continuous, but only more or less discontinuous.

4.2.3. Different attitudes toward phenomena. Phenomenon-based teachers typically take a different epistemological stance than model-based teachers: They disagree on whether objects would exist without an observer. In a questionnaire, German and Scandinavian experts on phenomenon-based instruction “have not agreed with the claim that ‘[…] there is a reality independent of perception or a perceiver (Realism)’” [4] (my translation). In contrast, German experts in model-based instruction have promoted (hypothetical) realism [14,15]. They argue that modeling would be pointless without pre-existing objects to be modeled [14].

At least, there is some common ground: Both parties reject naïve realism, the belief that subjects perceive objects as they truly are. Moreover, both parties accept constructivism [7,14]. Thus, they can enable their students to think of a model as a subjective representation of an independent object, even if they encourage their students to experience a phenomenon as an interplay between subject and object. Conceptions may surpass perceptions; and perceptions do exist, no matter what the subject believes about the existence of objects.

5. Conclusion

By definition, the criteria for phenomenon-based learning are diametrically opposed to those for model-based teaching (Tab. 1). At first sight, the two instruction methods seem incompatible.

Upon closer examination, the diametrically opposed criteria turn out to define two ends of a continuum (Fig. 3). Over time, the teacher can move along that continuum, guiding students from exploratory to more theory-laden experiments, from inductive to deductive reasoning, from descriptive to explanatory modeling, and from their everyday world to the world of physics. Thus, physics instruction may be phenomenon-based and model-oriented.

Some aspects of phenomenon-based instruction are already part of model-based methods, and some aspects of model-based instruction are already part of phenomenon-based methods. To integrate all aspects, the teacher needs a flexible attitude toward phenomena, teaching strategies, and models.

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7. References

[1] Silander P 2015 Phenomenal education (http://www.phenomenaleducation.info/phenomenon-based-learning.html)
[2] Kultusministerkonferenz 2004 Bildungsstandards im Fach Physik für den Mittleren Schulabschluss (https://www.kmk.org/fileadmin/Dateien/veroeffentlichungen_beschluesse/2004/2004_12_16-Bildungsstandards-Physik-Mittlere-SA.pdf)
[3] NGSS Lead States 2013 Next Generation Science Standards (https://www.nextgenscience.org)
[4] Westphal N 2014 Evaluation von phänomenbasiertem Physikuterrricht
[5] Westphal N, Schön L-H and Grebe-Ellis J 2011 Die Merkmale phänomenbasierten Physikunterrichts PhyDid B 2011 DD23.02 (http://www.phydid.de/index.php/phydid-b/article/view/282/336)

[6] Müller M 2017 Grammatik der Natur: Von Wittgenstein Naturphänomene verstehen lernen (Berlin: Logos)

[7] Theilmann F, Buck P, Murmann L, Østergaard E, Hugo A, Dahlin B, Aeschlimann U and Rittersbacher C 2013 Phänomenologische Naturwissenschaftsdidaktik ZfDN 19 397-416

[8] Østergaard E, Hugo A and Dahlin B 2007 From phenomenon to concept: Designing phenomenological science education 6th IOESTE Symposium for Central and Eastern Europe 123-9 (http://www.umb.no/statistik/larerutdanning/from_phenomenon_to_concept.pdf)

[9] Schwarz J F and Symeonidis V 2016 Phenomenon-based teaching and learning through the pedagogical lenses of phenomenology: The recent curriculum reform in Finland Forum Oświatowe 28(2) 31-47

[10] Østergaard E 2015 How can science education foster students’ rooting? Cult. Stud. of Sci. Educ. 10 515-25

[11] Murmann L 2008 Exploring natural phenomena EARLI-SIG (Kristianstad) (http://www.distans.hkr.se/sig9/download/download-filer/Full%20paper-%20L%20Murmann.pdf.)

[12] Østergaard E, Dahlin B and Hugo A 2008 Doing phenomenology in science education: A research review Studies in Science Education 44(2) 93-121

[13] Grebe-Ellis J 2006 Phänomenologische Optik: Eine “Optik der Bilder” Teil 1 chim. did. 32(97) 137-186

[14] Leisner-Bodenthin A 2006 Zur Entwicklung von Modellkompetenz im Physikunterricht ZfDN 12 91-109

[15] Mikelskis-Seifert S, Thiele M and Wünscher T 2005 Modellieren – Schlüsselfähigkeit für physikalische Forschungs- und Lernprozesse PhyDid A 1(4) 30-46

[16] Halloun I A 2007 Mediated modeling in science education Sci. & Educ. 16 653-97

[17] Windschitl M, Thompson J and Braaten M 2008 Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations Sci. Educ. 92 941-67

[18] Jackson J, Dukerich L and Hestenes D 2008 Modeling Instruction: An effective model for science education Sci. Educ. 17(1) 19-7

[19] Jonassen D, Strobej J and Gottdenker J 2005 Model building for conceptual change Interactive Learning Environments 13 15-37

[20] Passmore C, Stewart J and Cartier J 2009 Model-based inquiry and school science: Creating connections S. S. M. 109 394-402

[21] Schwarz C V and Gwekwerere Y N 2007 Using a guided inquiry and modeling instructional framework (EIMA) to support preservice K-8 science teaching Sci. Educ. 91 158-86

[22] White B Y and Frederiksen J R 1998 Inquiry, modeling, and metacognition: Making science accessible to all students. Cognition Instruct. 16(1) 3-118

[23] Chinn C and Malhotra B 2002 Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks Sci. Educ. 86 175-218

[24] Clement J 1988 Learning via model construction and criticism: Protocol evidence on sources of creativity in science (Amherst: Scientific Reasoning Research Institute) I-99 (http://files.eric.ed.gov/fulltext/ED303357.pdf)

[25] Fortus D, Shwartz Y and Rosenfeld S 2016 High school students’ meta-modeling knowledge Res. Sci. Educ. 46 787-810

[26] Oh P S and Oh S J 2011 What teachers of science need to know about models: An overview Int. J. Sci. Educ. 33 1109-30

[27] Campbell T, Oh P S and Neilson D 2012 Discursive modes and their pedagogical functions in model-based inquiry (MBI) classrooms Int. J. Sci. Educ. 34 2393-2419
[28] Campbell T, Schwarz C V and Windschitl M 2016 What we call misconceptions may be necessary stepping-stones toward making sense of the world 83(3) T. S. T. 69-74
[29] Krell M, Reinisch B and Krüger D 2015 Analyzing students’ understanding of models and modeling referring to the disciplines biology, chemistry, and physics Res. Sci. Educ. 45 367-93
[30] Uhden O, Karam R, Pietrocola M and Pospiech G 2012 Modelling mathematical reasoning in physics education Sci. & Educ. 21 485-506
[31] Pirnay-Dummer P, Ifenthaler D and Seel N M 2012 Designing model-based learning environments to support mental models for learning (Theoretical foundations of learning environments) ed D Jonassen and S Land (London: Routledge) pp 66-94
[32] Brewe E 2008 Modeling theory applied: Modeling Instruction in introductory physics Am. J. Phys. 76 1155-60
[33] Stephens A L and Clement J J 2007 Analyzing the use of teaching strategies in a model based curriculum: Promoting expert reasoning and imagery enhancement in high school students Proceedings of the NARST 2007 Annual Meeting (New Orleans, LA) pp 1-19
[34] Kawasaki K, Herrenkohl L R and Yeary S A 2004 Theory building and modeling in a sinking and floating unit: A case study of third and fourth grade students' developing epistemologies of science Int. J. Sci. Educ. 26(11) 1299-1324
[35] Clement J 2000 Model based learning as a key research area for science education Int. J. Sci. Educ. 22(9) 1041-53
[36] Davis J P and Bellocci A 2017 Objectivity, subjectivity, and emotion in school science inquiry J. R. S. T. 55(10) 1419-47
[37] Grusche S 2017 Developing students’ ideas about lens imaging: teaching experiments with an image-based approach Phys. Educ. 52(4) 044002
[38] Grusche S 2016 Seeing lens imaging as a superposition of multiple views Phys. Educ. 51 015006
[39] Grusche S and Wagner S 2016 Two different looks at Kepler’s refraction experiment Phys. Educ. 51 064001
[40] Erb R 1997 Designing an improved reflector Phys. Educ. 32 100
[41] Newton I 1979 Opticks (Mineola: Dover)
[42] Grusche S 2015 Revealing the nature of the final image in Newton’s experimentum crucis Am. J. Phys. 83 583-9
[43] Galili I and Hazan A 2000 The influence of an historically oriented course on students’ content knowledge in optics enhanced by means of facets-schemes analysis Am. J. Phys. 68 S3
[44] Kwan A M and Wardle D A 1998 Covering lenses and covering images T. P. T. 36(5) 314-5
[45] Duit R 1996 The constructivist view in science education – what it has to offer and what should not be expected from it Investigações em Ensino de Ciências 5(1) 40-75
[46] Posner G, Strike K, Hewson P and Gertzog W 1982 Accommodation of scientific conception: Toward a theory of conceptual change Sci. Educ. 66 211-227