

How to Support the Process of Forming Analogies to Facilitate Model-Building in Science Education

Dr. Michael Haider¹ & Marika Haider²

In the following article we illustrate the importance of learning with models and analogies in science education. Learning with models is both exciting and promotes greater comprehension capabilities, whilst an understanding of how the analogies model works, remains to be a very interesting topic also. The issue explains the process of forming models and describe how this process can be supported in the classroom. We describe the process of analogy formation and examine how far the use of specific models, can support the processes of analogy formation. A proficient handling of models plays an important role in this context. Therefore, the focus would be on model competence, learning with and learning about models. In addition, the process of modeling, will be explained and theoretical founded, on a circle of modelling postulated in mathematical didactics. The particular benefit of the following article is the merging of different views on modelling: psychology, pedagogy, natural scientific and mathematical didactics.

Keywords: modeling, model, competence, analogy

Analogies and transductive reasoning (Spreckelsen, 1997) play an important role in everyday life. They facilitate learning (see e.g., Black & Solomon, 1987; Dudeck, 1997; Haider, 2010) in general, and in science education they often are indispensable. Hesse (1991) categorizes analogies according to their function: assignment, understanding or problem solving. Forming analogies supports learning only if the learner himself establishes the analogy. This requires bringing various elements into relation and creating a mental model or analogous picture of reality to aid understanding.

1. How can the process of forming analogies support learning?

In primary science education, especially in physics, forming analogies often contributes to better understanding of various phenomena. Although forming analogies is a common way to support learning processes and its effectiveness is undisputed, it should be examined in individual cases.

Why does forming analogies support learning?

The relevance of analogies as a didactic tool in science is emphasized in various studies; however, these mostly involve learners at the secondary school level (exception: Haider, 2010) and present cognitive reasons for their use. According to Vosniadou, Ioannides, Dimitakopoulou and Papademetriou (2001) as well as Posner, Strike, Hewson and Gertzog (1982), analogies support conceptual change.

¹Lehrstuhl für Grundschulpädagogik, Universität Regensburg; Universität Regensburg, Institut für Pädagogik, Fakultät für Psychologie, Pädagogik und Sportwissenschaft, 93040 Regensburg, E-Mail: michael.haider@ur.de, Telephone: 0941 943-3426, Fax: 0941 943-3195

²Universität Regensburg, Institut für Pädagogik, Fakultät für Psychologie, Pädagogik und Sportwissenschaft, 93040 Regensburg E-Mail: marika.haider@ur.de, Telephone: 0941 943-3674, Fax: 0941 943-1992

Cognitive conflicts and analogical thinking have a complementary function in learning processes (Caravita, 2001) and analogies promote a deeper understanding of complex facts (Kurtz, Miao & Gentner, 2001). Further, the use of analogies allows a greater learning potential to be reached (Duit, Treagust & Widodo, 2008).

Gentner, Loewenstein and Thompson (2003) highlight the significance of such comparisons in the learning process and Duit and Glynn (1995) stress the importance of motivation, cause subjects who are using analogies can access to their knowledge. According to Black and Solomon (1987) the use of analogies in learning abstract matter can help underachievers gain quicker understanding and increase their self-confidence.

How can analogies be applied effectively?

Analogies (from Greek- *αναλογία*- meaning similarities) are meant to create relations between objects or processes by focusing on similarities. Initially, the existence of such relations is viewed as the analogy (see Figure 1).

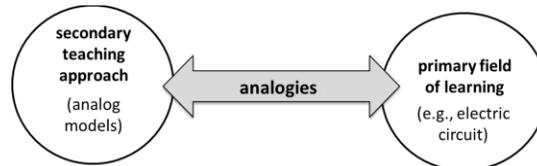


Fig. 1: Forming analogies (see e.g., Mikelskis-Seifert & Fischler, 2003; Gentner, 1980; Duit, 1995)

Analogies are differently. In science they are used to build new scientific research findings, in didactic they are used to explain already found results. Analogies in teaching - for example to describe electrical circuits - often are used to illustrate physical concepts more clearly and to support conceptual change. Visual representation can facilitate learners' understanding of such concepts and therefore are used as a didactic tool to illustrate something that in reality is too large, small, fast or slow. Analogies serve as an intermediary between "primary and secondary learning field of learning" (see also Gentner, 1988; Duit, Roth, Komorek & Wilbers, 2001).

This bridging function (Duit & Glynn 1995) or intermediary role (Kircher, 1995) can be explained in the following way: Pupils use their knowledge in a secondary field (e.g., Gentner, 1988) to draw analogous conclusions in or into a primary field of learning (see e.g., Hesse, 1991; Kircher, 1995; Duit & Glynn, 1995; Spreckelsen, 1997; Duit, 2001). This correlates with Weinert's ideas of "building intelligent knowledge" and "network knowledge" (2001). Drawing an analogous conclusion between the secondary and the primary field of learning by the learner itself, thus actively forming an analogy, is the basic of the intermediary function of learning with analogies. For this reason Kircher emphasizes the active role of the subjects (pupils) in forming analogies (see Fig. 2).

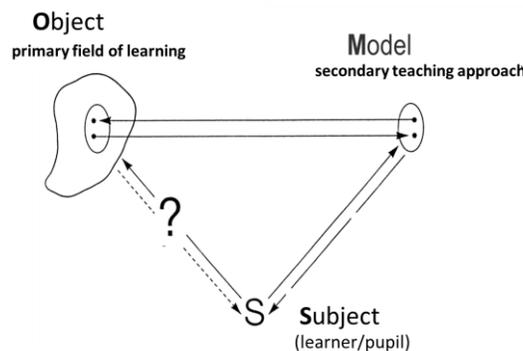


Fig. 2: Forming analogies including the pupil (Kircher, 1995)

When dealing with the secondary learning object an important factor is that the learner succeeds in developing mental models to draw parallels to the primary learning field. When a learner makes an analogy, he builds or models (abstract) ideas of the secondary teaching approach, by comparing or making parallels to the primary field of learning. Common analogous models are used to support this process. Here, 'model' refers to a specific object that becomes representative of the primary learning object.

Discussion on using analogies

Because analogies have advantages as well as disadvantages, they often are discussed in subject didactics literature (see e.g., “friend or foe”, Harrison & Treagust, 2006; “double-edged sword”, Glynn, 1989). According to Klauer and Leutner (2007) there is comprehensive empirical research that shows positive effects of analogies on learning processes; however, there also are studies that reveal learning difficulties resulting from the use of analogies. For example, it has been found that learning can be disturbed or handicapped by simplifications of analogies (‘analogies as crutches’, Kircher, 1995).

It has been shown that the choice of the analogous field restricts or even disturbs the processes of understanding. Misconceptions can occur when reductions or magnifications are perceived to be reality. One way to avoid this is to use multiple analogies (Duit & Glynn, 1995; “transductive understanding in phenomenon circles”, Spreckelsen, 1997). By drawing on what is known, new perspectives will be opened to understand the concept to be learned (see Duit & Glynn, 1995, p. 48). Multiple analogies help the pupil ascertain in what the reductions and simplifications consist.

Problems arising from the use of analogies indicate that analogical conclusions drawn from the secondary to the primary field of learning are not accurate and therefore pupils need more support. One way to help pupils in this case is the use of (concrete) models for visualization.

2. Externalized models to facilitate forming analogies

In 1973 Stachowiak published his general model theory in which he claimed that models have, to varying degrees, the principal characteristics of mapping, abbreviating and pragmatic feature. According to this theory, models map something that can be realized, for example, in iconic, objective or mental representations (e.g., the illustration of rays of light or the imagination of atoms in Bohr’s atomic model). At that, models do not include every characteristic or attribute of the originals they represent; they reduce them from a pragmatic perspective to the characteristics or attributes which are important for the modelmaker or modeluser. Models are not assigned to original concepts per se, but are assigned to the use of the models, the time of their use or their operations (Stachowiak, 1973). Various functions are attributed to models, for example simplifying, visualizing, building analogies, and simulating, in order to make predictions. Seel (1991) refers to these as *didactic functions* of models and transfers them to mental models. He attributes a didactic function in the process of explaining phenomena to a part of thinking (the building of mental models). On one hand these didactic functions of models make them suitable *tools* for teaching and learning, especially science (Kattmann, 2006). Gilbert (2004) describes the didactic functions as “*to be a model of something*”. On the other hand models as a *method* on the meta-level can become the content of the lessons themselves. Gilbert (2004) refers to this as “*to be a model for something*”. So, models have the double role of a medium and of a method in science education.

Models as representations of ideas about reality can focus on either appearance or structural similarities. For example, a model of the human eye used in lectures in biology looks similar to a real human eye; a model of the human eye with lenses arranged on an optical bench used in lectures in physics does not look like an eye at first glance, but merely shows its structure. In this way, the use of models differs. So depending on the objectives *superficial* or *structural similarities* can be accented. The aim of using models in teaching is to support the learning processes targeted. However, models can be used effectively in teaching only if pupils become competent in forming such models themselves (see section 3).

On terminology: analogy – model – analogous model

The terms *analogy* and *model* are used differently by researchers (see Mikelskis-Seifert, Thiele & Wünscher, 2005: “Babylonian language chaos,”; for additional terms see Lesh & Lehrer, 2003; Gentner, 1980; Hesse, 1991; Kircher, 1995, Grygier, Günther & Kircher, 2007). The term *model* is used in the following ways: as a prototype (e.g., models of cars in wind tunnels), an object (e.g., models of a steam engine), an example of something (e.g., models of a pilot experiment, a study path), a theory or concept (e.g. models of a ray of light); analogical models are used as a speciality of model, model is used as speciality of analogical model (the direction is not defined). Sometimes these terms are used synonymously or in the form of a connection as an *analogical model* (see e.g., Mikelskis-Seifert et al., 2005; Gentner, 1980; Duit, 1995). An analogical model is an objective representation of a theoretical model with which knowledge built in the secondary field of learning can be assigned to the primary field of learning via analogies.

It would be useful if the distinction between model and analogical model were determined by the domain: If a model allows an analogical conclusion to be drawn in another domain (e.g., a water circuit model used as a model for an electric circuit, see e.g., Kircher, 1995; Haider, 2010), it should be referred to as an *analogical model*. If a model is used to illustrate something in the same domain (e.g., a model of a ray of light to explain shadow formation), the term *model* should be used. Competence in forming and using models, also known as competence in modeling, is believed to contribute to a general understanding of science (Carey, 1985; Grosslight, Unger, Jay & Smith, 1991; Treagust, Chittleborough & Mamiala, 2002; Grygier, 2008) and therefore is required of pupils in Germany by the national educational standards (KMK 2004).

3. Learning with and about models

3.1 Competence in modelling in science education: definitions and demarcations

Competence in modeling is defined as the ability to deal with models to acquire knowledge and gain expertise (Upmeyer zu Belzen & Krüger, 2013, p. 7). Hodson (1992) explains that there are three main aims of scientific education: *learning science* (acquiring and developing conceptual and theoretical knowledge), *doing science* (engaging in and developing expertise in scientific inquiry and problem solving) and *learning about science* (developing an understanding of the nature and methods of science). Meisert (2008) seizes this approach for teaching biology and (analogous) distinguishes between competence in modeling from knowledge of models themselves, and between use of models and understanding models. At the conceptual level, *knowledge of models* involves recognition of basic scientific models.

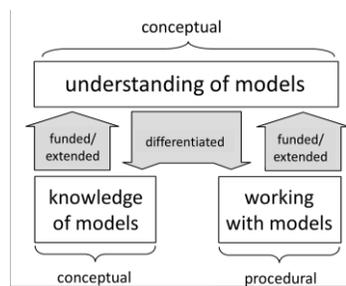


Fig. 3: Dimensions of competence in modelling and interdependencies (Meisert, 2008)

Use of models refers to the procedural competence to use or to develop (existing) models. *Understanding of models* refers to a superior dimension understood as part of an adequate nature-of-science-concept. In this Meisert sees an understanding of the significance of models and their use (ibid.). Considering pedagogical (Weinert, 1999) and psychological (Gerlman & Greeno, 1989) definitions of competence, Leisner (2005, 2006) defines competence of modelling in physics education as a learner's disposition to manage procedural and declarative demands in dealing with models at school. *Declarative knowledge* involves understanding models (knowledge of models as human constructions for explanations, predictions or visualizations; knowledge of abstractions when developing models; the purpose of models; the hypothetic and temporary nature of models) as well as knowledge of the content and characteristics of models, of certain suppositions and idealizations. The ability to apply declarative knowledge of models to solve problems is assigned to *procedural knowledge*. This component i.a. is characterized by the distinction between models and phenomena, by an appropriate selection, use and evaluation of models or by the reflection of models and modeling. The *degree of autonomy* appears in the practicability of declarative and procedural knowledge in varying and unknown situations. In addition Leisner-Bodenthin (2006) differentiates between *domain-specific* and *cross-domain* competence in modeling. Upmeyer zu Belzen and Krüger combine the above-mentioned approaches with findings from Crawford and Cullin (2005), Justi and Gilbert (2002) and Grosslight, Unger, Jay and Smith (1991) and define competence in modeling in biology education as follows: "competence in modeling includes the abilities to purposively acquire knowledge with the help of models and to evaluate models regarding their purpose, the abilities to reflect on the process of knowledge acquisition with models and modeling as well as the disposition to make use of these abilities in problematic situations" (Upmeyer zu Belzen & Krüger, 2010, p. 49).

Their approach differentiates between the rather declarative dimension *knowledge of models* and the rather procedural dimension *modeling*. The dimension *knowledge of models* distinguishes *characteristics of models* (rating of similarities or abstractions, relations between models and reality) from *alternative models* (questioning why there are

different models for one original object). The dimension *modeling* is expressed in the ability to acquire knowledge with models and includes the reflection of the modeling process as well as the opinion about models. The sub-competences *purpose, testing* and *changing* of models are associated with modeling.

Referring to Grosslight et al.'s (1991) three levels of thinking about models (1. naive understanding of models as either toys or simple copies of reality; 2. awareness of the purpose of models and the modeler's role, possible simplifications and highlightings; 3. models as modeler's constructions in service of developing and testing ideas), Upmeyer zu Belzen and Krüger (2010) graduate each of the five sub-competences into three levels distinguishing reflectiveness from main aspects of the models: Contemplations on models as autonomous objects (level I), creation of relations between original and model object (model of something, level II) and making use of models for predictions or gaining new knowledge (model for something, level III).

In summary, in the above-mentioned approaches to learning with and about models different terms are used to refer to the sub-components of competence in modeling. However, accordance's can be found regarding what competence in modeling is: The approaches each describe *declarative elements* (knowledge of models) and *procedural elements* (working with models) as dimensions of competence in modelling and – even though it is not always explicitly mentioned as a single facet – refer to the *reflection on models* (significance, nature and validity of models). The three components thereby can be developed both domain-specific, that is, in terms of a *general competence in modeling* (when models are thematized on a rather abstract level) and cross-domain, thus as *specific competences in modelling* (when dealing with particular models). The above approaches have been developed almost entirely with reference to secondary school pupils. However, basic elements of competence in modelling also are likely to be achieved in science education in primary school. In Terzer's (2013) study even students in secondary school usually do not achieve level III. Based on existing approaches for secondary school learners, the following subareas can be cited for learning with and about models in science class in primary school:

Table 1:
Categorization of competence in modelling in primary school

		COMPETENCE IN MODELING		
COMPETENCE IN BUILDING SPECIFIC MODELS	COMPETENCE IN BUILDING	<i>Declarative knowledge</i> of models (knowledge of models)	<i>Procedural knowledge</i> of models (use of models)	<i>Reflection</i> on models (significance and nature of models)
	SPECIFIC MODELS	Model – Non-model differentiation Characteristics of models (similarities, differences, simplifications, idealizations) Types of models and forms of realization	Application of models for knowledge acquisition Transfer between models and reality	Purpose of models Validity and limitations of models

3.2 Process of modeling

In the literature the term of *modeling* is not clearly identified. In some research, the development or construction of models is meant. This is normally what is meant in the Anglo-American literature (e.g., Schwarz et al., 2009). In various disciplines and to various authors (e.g., Schupp, 1988; Seel, 1991; Martschinke, 1993; Blum, 1993; Barwanietz, 2005) the term *modelling* not only refers to the construction of a model, but means the whole process of developing model of reality in one's mind. So it also includes processes of learning and understanding (or parts of it), in which the learner builds images and explanations of phenomena. Therefore learners' observations are synchronized with existing knowledge and explanatory approaches are created. Mental models are created for observations, which network new and already existing knowledge. The theory of modeling can be founded on theory of constructivism here.

The ability to explain a model depends on a person's ability to form a model in a specific situation. The ability to build a model for scientific purposes means – similar to building a model for mathematic purposes (Barwanietz, 2005) – the ability to connect an existing model with a new problematic situation (a new phenomenon) through cognitive activities. This means that the learner connects a real situation (the phenomenon or everyday appearance) with scientific explanations, relations and terms in mind.

Modeling as learning process

People perceive situations and phenomena in various ways. Influenced by previous experiences, individual precognitions, and classifications in the individuals' own semantic networks, phenomena are interpreted and explained. However, the perception does not sort the phenomena in a specific domain. A rainbow, for example, does not allow people to think in physical contexts (concerning the reflection of light) or in psychological contexts (concerning the impact of different colors). Phenomena can be perceived from various perspectives. Pupils' perspectives on their own lives are not weighted but are standing side by side. To explore and to be able to explain phenomena requires asking specific questions that lead to observation and classification in disciplines, as is understood at secondary school. For example, when exploring the formation of a rainbow, physical approaches must be taken. In this particular case a connection must be made to light refracting at a rain front.

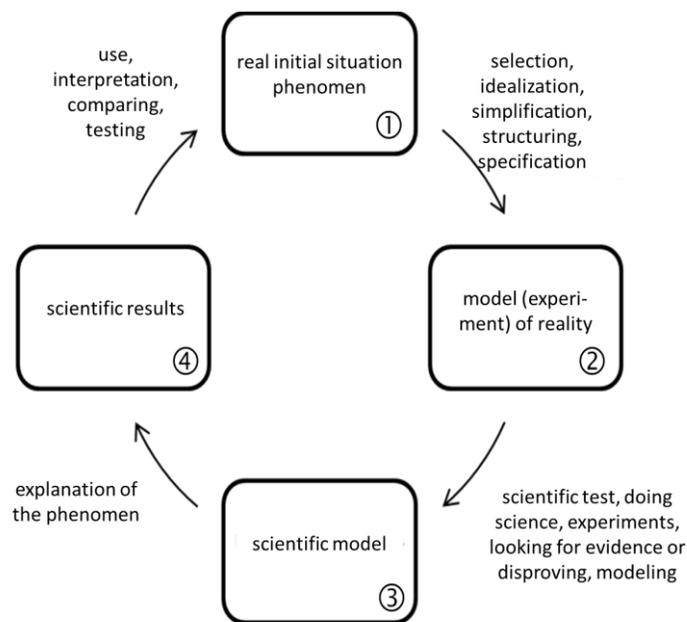


Fig. 4: Structure of scientific modeling

Creating a model for mathematic purposes (Barwanietz, 2005; Blum, 1993; Schupp, 1988) is similar to creating one for scientific purposes, and the structure can be described as follows (see Figure 4): (1) First, *areal starting position, a phenomenon* is perceived by the sense organs. Usually this perception is made in a real situation which is influenced in its complexity by several factors. In order to explain a phenomenon it is necessary to filter the information and select central aspects. Simplifications (e.g., not such complex or idealized experimental designs) could be helpful at this point in the learning process. To explain the phenomena, central aspects (e.g., light rays refracted by a rainbow) are selected and simplifications (e.g., reducing to refraction at singular rain drops) are made. Focusing is given central importance (see also Einsiedler & Hardy, 2010; Hardy, 2012; Haider, Keck, Haider & Fölling-Albers, 2012).

(2) Similar to the approach in mathematics didactics, the reality of a phenomenon has to be recreated in a *model* (in science education perhaps in the form of a *model experiment*). For example, to recognize the appearance of a rainbow, pupils can explore the physical process of light rays refracting at a singular rain drop. Such a model experiment does not illustrate reality as a whole, but is created from a real phenomenon from a certain (here physical) perspective.

The model or the model experiment represents only those aspects which are objective (see real model in the mathematics didactics model: Henn, 1997; Barwanietz, 2005). Pupils' own hypotheses can be examined with the model.

(3) In a subsequent step the learner tries to gain abstract insight through the model experiment and examine it scientifically. With experiments and transfer in an abstract *scientific model* (e.g., the model of light rays refracting for a rainbow to appear) an attempt is made to explain the functioning – or at least part of it.

(4) With the help of models to formulate *scientific results*, new phenomena can be explained or perhaps the same phenomena can be explored, compared or tested. The modeling circle can be made repeatedly if need to (see mathematics didactics: Blum, 1996; Schupp, 1988; vom Hofe, 2003; Barwanietz, 2005).

4. Conclusion

Analogies are an important tool for both knowledge acquisition in science and knowledge transfer or explanation of phenomena in didactics. Analogical models seem to be an appropriate tool for initiating analogical conclusions. Because of their didactic functions, analogical models – as a particular type of model – provide links for learners. Analogies in science can activate a learning process which often requires modeling real phenomena. In order to succeed in interpreting and explaining such phenomena, the complex reality needs to be simplified, structured or specified via models. Modeling can be embedded in cognitive psychology approaches which support theories of assimilation and accommodation. According to these approaches, mental models are created when spontaneous explanations based on existing knowledge are found. This cognitive construction – or interpretation of the world – needs to be investigated for plausibility. For pupils to be able to use specific models or analogical models effectively as learning tools they have to develop competence in dealing with them. This means that both general and specific competence in forming and using models can be applied to understand and explain phenomena. A structurally sound model of competence in modelling and its facets remains to be created.

Bibliography

- Barwanietz, T. (2005). Die Förderung der Modellierungsfähigkeit im Mathematikunterricht der Grundschule. - Der Einfluss alltagsnaher und abstrakt-symbolischer Handlungsorientierung auf die mathematische Modellierungsfähigkeit und die Lernmotivation von Grundschulkindern. Dissertation, Universität Regensburg, <http://epub.uni-regensburg.de/10365/>
- Beinbrech, C. (2003). Problemlösen im Sachunterricht der Grundschule, eine empirische Studie zur Gestaltung von Lehr- Lernumgebungen im Hinblick auf die Förderung des Problemlöseverhaltens im Sachunterricht. Dissertation, Westfälische Wilhelms-Universität Münster.
- Black, D. & Solomon, J. (1987). Can pupils use taught analogies for electric current? *School Science Review*, 69, 249-254.
- Blum, W. (1993). Anwendungen und Modellbildung im Mathematikunterricht. Hildesheim: Franzbecker.
- Blum, W. (1996). Anwendungsbezüge im Mathematikunterricht - Trends und Perspektiven. Beiträge zum 7. internationalen Symposium zur Didaktik der Mathematik, 15-38.
- Caravita, S. (2001). A re-framed conceptual change theory? – Commentary. *Learning and Instruction*, 11, 421-449.
- Carey, S. (1985). *Conceptual change in childhood*. Cambridge, MA: MIT Press.
- Crawford, B. & Cullin, M. (2005). Dynamic assessments of preservice teachers' knowledge of models and modeling. In K. Boersma, H. Eijkelhof, M. Goedhart & O. Jong (Eds.), *Research and the Quality of Science Education* (pp. 309–323). Dordrecht: Springer.
- Dudeck, W.-G. (1997). Analyse von Denkprozessen in einem analogieorientierten Elektrizitätslehreunterricht - Fallstudie in einer 10. Gymnasialklasse. Aachen: Mainz.
- Duit, R. (1995). Analogien unter der Lupe. *Naturwissenschaften im Unterricht. Physik*, 6(43), 11-14.
- Duit, R. & Glynn, S. (1995). Analogien - Brücken zum Verständnis. *Naturwissenschaften im Unterricht. Physik*, 6(43), 4-10.
- Duit, R., Roth, W.M., Komorek, M. & Wilbers, J. (2001). Fostering Conceptual Change by Analogies - Between Scylla and Carybdis. *Learning and Instruction*, 11, 283-303.
- Duit, R., Treagust, D. & Widodo, A. (2008). Teaching Science for Conceptual Change: Theory and Practice. In S. Vosniadou (Ed.), *International Handbook of Research on Conceptual Change* (pp. 629-646). New York, London: Routledge.
- Einsiedler, W. & Hardy, I. (2010). Kognitive Strukturierung im Unterricht. Einführung und Begriffsklärungen. *Unterrichtswissenschaft*, 38(3), 194-209.
- Gelman, R. & Greeno, R. (1989). On The Nature of Competence: Principles for Understanding in a Domain. In L. B. Resnick (Ed.), *Knowing, learning and instruction* (pp. 125-186). Hillsdale: Routledge.
- Gentner, D. (1980). The structure of analogical models in science. Cambridge, Mass: Bolt Beranek and Newman.
- Gentner, D. (1988). Analogical inference and analogical access. In A. Prieditis (ed.), *Analogica* (pp. 63-88). Los Altos: Morgan Kaufmann Publishers.
- Gentner, D., Loewenstein, J. & Thompson, L. (2003). Learning and Transfer: A General Role for Analogical Encoding. *Journal of Educational Psychology*, 95(2), 393-408.

- Gilbert, J. (2004). Models and Modeling: Routes to More Authentic Science Education. *International Journal of Science and Mathematics Education*, 2, 115-130.
- Glynn, S. M. (1989). The teaching with analogies (F.W.A.) model: explaining concepts in expository text. (M. K. D., Ed.) *Children's comprehension of narrative and expository text: Research into practice*, 99-129.
- Grosslight, L., Unger, C., Jay, E. & Smith, C. (1991). Understanding models and their use in science: Conceptions of middle and high school gradents and experts. *Journal of Research in Science Teaching*, 12, 799-822.
- Grygier, P. (2008). *Wissenschaftsverständnis von Grundschulern im Sachunterricht*. Bad Heilbrunn: Klinkhardt.
- Grygier, P., Günther, J. & Kircher, E. (Eds.). (2007). *Über Naturwissenschaften lernen – Vermittlung von Wissenschaftsverständnis in der Grundschule (2nded.)*. Baltmannsweiler: Schneider Verlag Hohengehren.
- Haider, M. (2010). *Der Stellenwert von Analogien für den Erwerb naturwissenschaftlicher Erkenntnisse*. Bad Heilbrunn: Klinkhardt.
- Haider, M., Keck, M., Haider, T. & Fölling-Albers, M. (2012). Die Rolle von Modellen für die Strukturierung naturwissenschaftlicher Lernprozesse. In F. Hellmich (Ed.), *Bedingungen des Lehrens und Lernens in der Grundschule* (pp. 217-220) Wiesbaden: VS-Verlag.
- Hardy, I. (2012). Kognitive Strukturierung - Empirische Zugänge zu einem heterogenen Konstrukt der Unterrichtsforschung. In F. Hellmich, F. Hoya, & S. Förster (Eds.), *Bedingungen des Lehrens und Lernens in der Grundschule - Bilanz und Perspektiven*. Jahrbuch Grundschulforschung (pp. 51-64). Wiesbaden: Springer VS.
- Harrison, A. G. & Treagust, D. (2006). Teaching and Learning with Analogies: Friend or Foe. In J. B. Aubusson (Ed.), *Metaphor and Analogy in Science Education* (pp. 11-219). Berlin: Springer (Netherlands).
- Henn, H. W. (1997). Mathematik als Orientierung in einer komplexen Welt. *Der Mathematikunterricht*, 5, 6-13.
- Hesse, F. W. (1991). *Analoges Problemlösen: eine Analyse kognitiver Prozesse beim analogen Problemlösen*. Weinheim: Psychologie-Verlags Union.
- Hodson, D. (1992). In search of a meaningful relationship: An exploration of some issues relating to integration in science and science education. *International Journal of Science Education*, 14, 541-562.
- Justi, R. S. & Gilbert, J. K. (2002). Modeling, teachers' views on the nature of modeling, and implications for the education of modellers. *International Journal of Science Education*. 24(4), 369-387.
- Kattmann, U. (2006). Modelle. In H. Gropengießer, & U. Kattmann (Eds.), *Fachdidaktik Biologie (7th ed.)*. Köln: Aulis Verlag Deubner.
- Kircher, E. (1995). Analogien im Sachunterricht der Primarstufe. *Sachunterricht und Mathematik in der Primarstufe*, 23(5), 192-197.
- Klauer, K. & Leutner, D. (2007). *Lehren und Lernen. Einführung in die Instruktionspsychologie*. Weinheim: Beltz-PVU.
- KMK (2004). *Bildungsstandards in Physik für den mittleren Schulabschluss*. Bonn: Kultusministerkonferenz.
- Kurtz, K., Miao, C.-H. & Gentner, D. (2001). Learning by Analogical Bootstrapping. *The Journal of the Learning Sciences*, 10(4), 414-446.
- Leisner-Bodenthin, A. (2006). Zur Entwicklung von Modellkompetenz im Physikunterricht. *Zeitschrift für Didaktik der Naturwissenschaften*, 12, 91-109.
- Leisner, A. (2005). *Entwicklung von Modellkompetenz im Physikunterricht*. Berlin: Logos.
- Lesh, R. & Lehrer, R. (2003). Models and modeling perspectives on the development of students and teachers. *Mathematical Thinking and Learning*, 5 (2&3), 109-129.
- Martschinke, S. (1993). Der Aufbau von Wissensstrukturen im Sachunterricht der Grundschule durch unterschiedliche bildliche Präsentationen. Darstellung einer Pilotstudie. In Ch. Tarnai (Ed.), *Beiträge zur empirischen pädagogischen Forschung* (pp. 101-114). Münster/New York: Waxmann.
- Meisert, A. (2008). Vom Modellwissen zum Modellverständnis - Elemente einer umfassenden Modellkompetenz und deren Fundierung durch lernerseitige Kriterien zur Klassifikation von Modellen. *Zeitschrift für Didaktik der Naturwissenschaften*, 14, 243-261.
- Mikelskis-Seifert, S. & Fischler, H. (2003). Die Bedeutung des Denkens in Modellen bei der Entwicklung von Teilchenvorstellungen - Stand der Forschung und Entwurf einer Unterrichtskonzeption. *Zeitschrift für Didaktik der Naturwissenschaft*, 9, 75-88.
- Mikelskis-Seifert, S., Thiele, M. & Wünscher, T. (2005). Modellieren – Schlüsselfähigkeit für physikalische Forschungs- und Lernprozesse. *PhyDid (Online-Zeitschrift)*, 4(1), <http://www.phydid.de>.

- Posner, G. J., Strike, K. A., Hewson, P. & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, 66, 211-227.
- Schupp, H. (1988). Anwendungsorientierter Mathematikunterricht in der Sekundarstufe zwischen Theorie und neuen Impulsen. *Mathematikunterricht*, 34, 5-16.
- Schwarz, C., Reiser, B., Davis, E., Kenyon, L., Achér, A., Fortus, D., Shwartz, Y., Hug, B. & Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching*, 46(6), 632-654.
- Seel, N. M. (1991). *Weltwissen und mentale Modelle*. Göttingen: Verlag für Psychologie Hogrefe.
- Soostmeyer, M. (1978). *Problemorientiertes Lernen im Sachunterricht*. Paderborn: UTB Schöningh.
- Spreckelsen, K. (1997). Phänomenkreise als Verstehenshilfe. In W. Köhnlein, B. Maquardt-Mau, & H. Schreier (Eds.), *Kinder auf dem Weg zum Verstehen* (pp. 11-127). Bad Heilbrunn: Klinkhardt.
- Stachowiak, H. (1973). *Allgemeine Modelltheorie*. Wien: Springer.
- Terzer, E. (2013). *Modellkompetenz im Kontext Biologieunterricht – Empirische Beschreibung von Modellkompetenz mithilfe von Multiple-Choice Items*. Dissertation, Humboldt-Universität zu Berlin. <http://edoc.hu-berlin.de/dissertationen/terzer-eva-2012-12-19/PDF/terzer.pdf>
- Treagust, D. F., Chittleborough, G. & Mamiala, T. L. (2002). Students' understanding of the role of scientific models in learning science. *International Journal of Science Education* (24), 357-368.
- Upmeyer zu Belzen, A. & Krüger, D. (2010). Modellkompetenz im Biologieunterricht. *Zeitschrift für Didaktik der Naturwissenschaften*, 16, 41-57.
- Upmeyer zu Belzen, A.; Krüger, D. (2013). Lernen mit Modellen. *Grundschule*, 6, 6-9.
- vom Hofe, R. (2003). Grundvorstellungen und Grundbildung (Basisartikel). *Mathematik lehren*, 3, 4-8.
- Vosniadou, S., Ioannides, C., Dimitrakopoulou, A., Papademetriou, E. (2001). Designing learning environments to promote conceptual change in science. *Learning and Instruction*, 11, 381-419.
- Weinert, F. E. (1999). *Concepts of Competence. Definition and Selection of Competencies: Theoretical and Conceptual Foundations (DeSeCo)*. München.
- Weinert, F. E. (Ed.) (2001). *Leistungsmessungen in Schulen*. Weinheim: Beltz.

Figure legend

Fig. 1: Forming analogies (see e.g., Mikelskis-Seifert & Fischler, 2003; Gentner, 1980; Duit, 1995)

Fig. 2: Forming analogies including the pupil (Kircher, 1995)

Fig. 3: Dimensions of competence in modeling and interdependencies (Meisert, 2008)

Fig. 4: Structure of scientific modeling