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

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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 issueexplains the process of formingmodels and describe how this processcan be supported in the classroom. We describe the processof 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 scientifical 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, andin science education they often are indispensable. Hesse (1991) categorizes analogies according to their function: assignment, understanding orproblem solving. Forming analogies supports learning only if the learner himself establishes the analogy. This requires bringing variouselements 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,forminganalogies often contributes to better understanding of variousphenomena. Although forming analogies is a common way to support learning processes and itseffectiveness is undisputed,itshould be examined in individual cases.

Why does forming analogies support learning?

The relevance of analogies as a didactic toolin science is emphasized in various studies;howeverthese mostlyinvolvelearners at the secondary school level (exception: Haider, 2010) and presentcognitive 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.

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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 inthe 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 underachieversgain quicker understanding and increase their self-confidence.

How can analogies be appliedeffectively?

Analogies (from Greek- ααναλογια- 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).

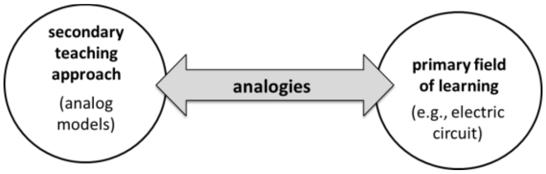

Fig. 1: Forminganalogies (see e.g.,Mikelskis-Seifert & Fischler, 2003; Gentner, 1980; Duit, 1995)

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 exampleto describe electrical circuits - often are usedto 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 toolto 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 ananalogous 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).

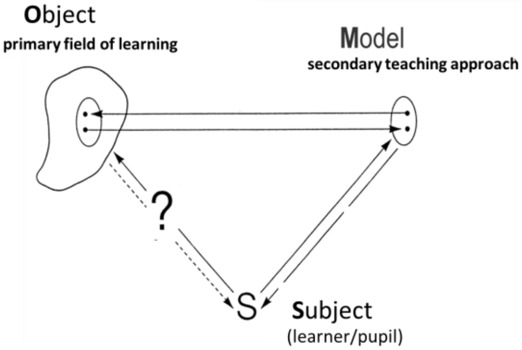

Fig. 2: Forminganalogies including the pupil (Kircher, 1995)

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. Whenalearner makes an analogy, he buildsor 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 ofthe analogousfield 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 conceptto 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 analogiesindicate 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 facilitateforming analogies

In 1973 Stachowiak published hisgeneral model theory in which he claimed thatmodels have, to varying degrees, the principal characteristicsof 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 donot 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 explainingphenomena 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 functionsas "*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 andofa method in science education.

Models as representations of ideasabout reality can focus on eitherappearance or structuresimilarities. 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 eyewith lenses arranged on an optical bench used in lectures inphysics doesnot look like an eye at first glance, but merely shows its structure. In this way, the use of models differs. Sodepending on the objective*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 becomecompetent in forming such models themselves (see section 3).

On terminology: analogy – model – anologous model

The terms *anology*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 ofcars in wind tunnels),an object (e.g., models of a steam engines),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 modelis 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 learningcan 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 illustratesomethingin 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 usingmodels, 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 dealwith models to acquire knowledge andgain expertise(Upmeierzu Belzen & Krüger, 2013, p. 7). Hodson(1992)explains that there are three mainaims of scientific education: *learning* science (acquiring and developing conceptual an 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*involvesrecognition of basic scientific models.

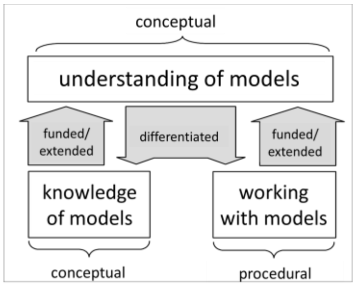

Fig. 3: Dimensions of competence in modelling and interdependencies (Meisert, 2008)

*Use of models*refers tothe procedural competence to use or to develop (existing)models. *Understandingof models*refers toa superior dimension understood as part of an adequate nature-of-science-concept. In this Meisert sees an understanding of the significance of models and theiruse (ibid.). Considering pedagogical (Weinert, 1999) and psychological (Gerlman & Greeno, 1989) definitions of competence, Leisner (2005, 2006) defines competence of modelling inphysics education as a learner's disposition to manage procedural and declarative demands in dealing with models at school.*Declarative knowledge* involvesunderstanding 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 distinctionbetween 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. Upmeierzu Belzenand Krüger combine the above-mentioned approaches withfindings from Crawford and Cullin (2005), Justi and Gilbert (2002)andGrosslight, 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" (Upmeierzu 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 forone 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 orsimple copies of reality; 2. awareness of the purpose of modelsand the modeler's role, possible simplifications and highlightings; 3. models as modeler's constructions in service of developing and testing ideas), Upmeierzu Belzen and Krüger (2010) graduate each ofthe five sub-competences into three levels distinguishing reflectiveness frommain 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 – referto 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 withreference to secondary schoolpupils. 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 usuallydo not achieve level III. Based on existing approaches for secondary schoollearners, 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	*Declarative knowledge*of models (knowledge of models)	*Procedural knowledge* of models (use of models)	*Reflection* on models (significance and nature of models)
	Model – Non-modeldifferentiation 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	Purposeofmodels Validity and limitations of models

3.2 Process of modeling

In the literature the term of *modeling* is not clearly identified.In some research,thedevelopment 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 learnerbuilds images and explanations of phenomena. Thereforelearners' 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 anexistingmodel 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 doesnot sort the phenomena in a specific domain. A rainbow,for example,doesnot 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, whenexploring the formation of a rainbow, physical approaches must be taken. In this particular casea connection must be made to light refracting at a rain front.

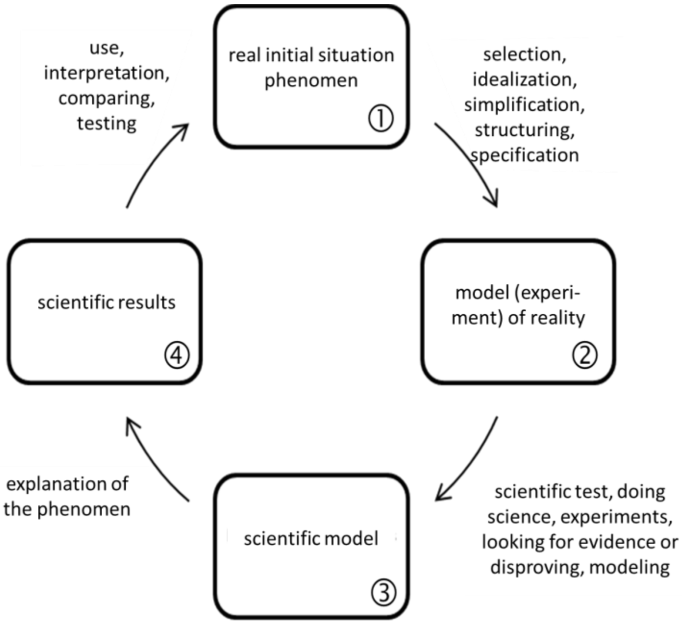

Fig. 4: Structure of scientific modeling

Creatinga model for mathematic purposes (Barwanietz, 2005; Blum, 1993; Schupp, 1988) is similarto creating one for scientificpurposes, and the structure can be described as follows (see Figure 4): (1) First, a*real 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 recreatedin *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 doesnot 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 realmodel in the mathematics didactics model: Henn, 1997; Barwanietz, 2005). Pupils' ownhypotheses can beexamined withthe 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 phenomenacan be explored, compared or tested. The modeling circle can be made repeatedly if needto (see mathematics didactics: Blum, 1996; Schupp, 1988; vomHofe, 2003; Barwanietz, 2005).

4. Conclusion

Analogies are an important toolfor 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 theirdidactic functions, analogical models – as a particular type of model – providelinks for learners.Analogies in science can activate a learning process which often requires modeling real phenomena. In order to succeed in interpreting and explaining suchphenomena, the complex reality needs to be simplified, structured or specified via models. Modeling can be embedded in cognitive psychology approaches whichsupporttheories 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 – needsto be investigatedfor plausibility.For pupilsto be able touse 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 modelscan be applied to understand and explain phenomena. A structurally sound model of competence in modelling and its facets remains to be created.

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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