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Fostering conceptual change by analogies— between Scylla and Charybdis

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Abstract

A growing body of research shows that analogies may be powerful tools for guiding students from their pre-instructional conceptions towards science concepts. But it has also become apparent that analogies may deeply mislead students' learning processes. Conceptual change, to put it into other words, may be both supported and hampered by the same analogy. The study presented here was designed to investigate the processes of analogy generation and development and to reveal the microstructure of analogical reasoning. Analogical reasoning was investigated during a grade 10 physics unit on the limited predictability of chaotic systems. Analogies played a key role in the instructional module to make explicit function and structure of certain chaotic systems. Analogies were also used to introduce the notion of "chaotic systems" embracing prototypical examples of chaotic systems studied. The theoretical orientation of the study merges key features of conceptual change approaches and social-constructivist studies on communities of learners. Hence, students were provided with substantial periods of time to generate their own analogies or employ analogies provided by the teacher to understand chaotic systems. There are many cases in our study that illustrate the affordances and pitfalls of analogies in promoting conceptual change. Hence the use of analogies as teaching and learning aids may always be a delicate course between Scylla and Charybdis. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Analogies and learning science

Analogies played a key role in the historical development of scientific knowledge (Hesse, 1966). However, learning by analogies occurs not only in scientific contexts. People in all walks of life often construct spontaneous analogies to understand unfamiliar issues in terms of familiar ones. Analogies appear to be powerful tools for learning science in schools. The use of analogies as learning aids is recommended especially in cases where students' pre-instructional conceptions and the science concepts are (partly) incompatible, that is, where conceptual change is necessary. But there are also studies which show that analogies may fail to bring about conceptual change and may even mislead students' thinking and learning processes (Duit, 1991; Glynn, Duit, & Thiele, 1996). Hence, analogies in school science may be "doubled-edged swords" (Glynn, 1989) that afford or constrain conceptual change depending on the circumstances.

1.1. On the concept of analogies

The term analogy is given different meanings with a certain overlap in the literature. The concept of analogy underlying the present paper is outlined in Fig. 1. An analogy involves the mapping of two domains called base and target. Certain features (aspects) are similar in both situations and constitute the analogical relation. There are two kinds of aspects that may be similar in base and target: (a) simple properties or surface features such as geometrical appearances or color or (b) deep features or structural properties. Some authors use the notion of analogy only when similarities are based on deep features as they usually have a greater explanatory power than surface similarities (e.g. Gentner, 1989). But surface features may also be important in learning by analogy as they can sometimes guide the learner's attention to the deeper structural similarities (Gentner & Landers, 1985).

Analogical relations are generally based on a *symmetry* between base and target. Base and target can each be viewed as an analogy for the other. This symmetry is of key importance in learning through analogies because the base frequently is equally unfamiliar to students. However, the symmetrical relations allow a stepwise construction of mutually constitutive understandings of both domains (Gooding, 1990). Learning by analogy is therefore not merely a one-directional process but includes switching perspectives between the two parts of the analogy. The permanent switch

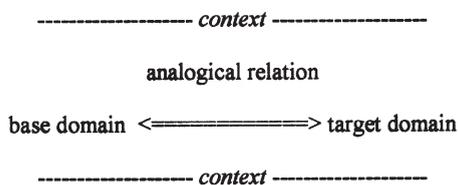


Fig. 1. Analogy: relation between base and target domain—embedded in a certain context.

of perspectives is also of key importance as it allows an understanding to develop the context in which the analogical relation is embedded.

1.2. Analogies and conceptual change

Analogical reasoning is a key feature of learning processes within a constructivist perspective: every learning process includes a search for similarities between what is already known and the new, the familiar and the unfamiliar (Wittrock & Alesandrini, 1990). In Rumelhart and Norman's (1981) theory of learning, which echoes Piagetian assimilation and accommodation, analogies play a key role. New schemata (conceptual frames) arise through either continuous development of already existing schemata or discontinuous reconstruction of already existing schemata. New conceptual frames are developed, transferring structures from familiar to new domains, that is, by establishing an analogy between the familiar and the unfamiliar. Conceptual change researchers have adopted Rumelhart and Norman's (1981) distinction between continuous growth and discontinuous change (Vosniadou, 1994; Schnotz, Vosniadou, & Carretero, 1999). Conceptual change perspectives have shown to be fruitful particularly in science education where everyday views of phenomena are often incommensurable with canonical views. Learning processes therefore often require major restructuring of students' already existing conceptions. Analogies can play a central role in this restructuring of students' conceptual frameworks. Sometimes, the base domain is as unfamiliar to students as the target domain. Students' understandings of the base domain therefore also require major restructuring. However, the symmetrical nature of the analogy relation may provide the possibility for "simultaneous" development of base *and* target a process of "piggy-backing" (Bereiter, 1985).

1.3. Discourse analytical view of analogies and learning

The discourse analytical approach employed in the present study is grounded in an epistemology that includes as its major concepts "observation sentences", "observation categoricals", "theoretical sentences", and "intersubjectivity" (Quine, 1992). Observation sentences link language and the world that language is about. Intersubjectivity is achieved when an observation sentence commands the same verdict from linguistically competent witnesses of an event and observation sentences become matters of fact. Because observation sentences and theoretical sentences share words, there is an automatic connection and interplay between the two forms of sentences. From this perspective, asserting that students experienced conceptual change is equivalent to saying that students utter different theoretical (and observation) sentences in their explanations of some event.

There are at least three forms of learning in the discourse analytical framework relevant to learning by analogies in open-inquiry lessons. First, students appropriate existing language beginning with observation sentences, "the entering wedge in the learning of language" (Quine, 1992, p. 5). Laboratory activities provide the opportunities to construct and negotiate fruitful observation sentences. Teachers who

engage with groups of students in conversations about events can thereby assist students in constructing observation sentences that later lead to students' construction of scientifically correct theoretical sentences (Roth, 1995a). Second, learning can occur when people construct new observation sentences, observation categoricals, and theoretical sentences as they engage in investigations. Historical studies of scientists at work and phenomenological studies of physics students showed how scientists and students learned as they modified observation sentences and phenomena until these were congruent (Gooding, 1990; Roth, 1996; Roth, McRobbie, Lucas, & Bou-tonné, 1997a). Third, learning can occur through analogical extension of existing observation sentences from exemplars to new situations followed by testing and use of existing theoretical sentences in the target domain (Wittgenstein, 1958).

This framework allows us to outline potential constraints of learning through analogical extension. Analogy rests on the similarity between observational sentences about the base and target domains. But similarity is difficult to pin down because it is tied to enumerating—in the form of observation sentences—the properties of two situations to be compared (Quine, 1987). As individuals bring to each situation an interpretive horizon shaped by past experiences, culture, and local contingencies (Heidegger, 1977), there exists an infinite number of observation sentences for base and target situation (the embedding context represented in Fig. 1). Unless the lists of observation sentences for base and target situation are highly congruent, learning by analogical extension from exemplars is difficult.

1.4. Analogies as seen by teachers, learners, and researchers

To understand learning by analogy, three perspectives need to be considered: those of analogy providers (teachers, textbook authors), learners, and researchers. First, within specific communities of practice members already share a lot of (tacit) background that contextualizes analogies. In these communities, there exist high degrees of intersubjectivity as to analogies and analogical relations are clearly defined and understood. In this case, analogies no longer serve heuristic functions. All analogical relations have fixed meanings so that one can speak of *post-festum* analogies. Most analogies provided in instructional situations—that is, analogies used in an *educational function*—are of this kind. The analogical relations have a clear and fixed meaning from the perspective of the analogy provider. These meanings are often not shared with the students.

Second, students are in a different position than teachers and textbook authors. Both base and target analogy may be viewed differently by learners and teachers (that is, bring about different observation sentences). Students therefore may not “see” the analogy at all.¹ If teaching and learning are to be successful at all, intersubjectivity has to exist between teachers (analogy providers) and students. Teachers

¹ Students frequently see different things than their teachers even when observing the “same” event (Roth, 1995a; Roth et al., 1997a). However, many science teachers do not seem to be sensitive enough and falsely assume that students share their visual experience.

and students therefore have to investigate the other party's understanding so that they can find a basis for communication. This communication will, in most cases, be by means of the everyday language game that teachers and students are likely to share by default (Roth, 1995a). It can be expected that students' analogical reasoning processes will be complex, including (from the perspective of the outsider) detours and blind alleys. However, the complexity of these processes is often reduced because of the instructional situations that encourages learners to assume that there should be some relation between base and target. Besides guided analogy use, science students are sometimes asked to construct their own analogies.

If students are asked to construct their own analogies for some phenomenon (Wong, 1993a,b; Kaufmann, Patel, & Magder, 1996), they also have to seek similarity relations. That is, from students' perspectives, analogies have a heuristic function allowing them to construct analogical relations and therefore deeper understandings of base and target situations. These analogical relations, however, are between the target and the students' self-generated base. Students will then construct similarity relations based on their observational sentences of the base and target. These descriptions are often different from those of the teacher. "Self-generated analogies" may therefore be based on analogical relations that teachers, who arranged such self-generation sessions, do not understand.

Third, researchers take a different position than students and teachers. Because our research investigates the development of analogical reasoning processes at a micro-level, the researcher has to be seen as an outside observer of the communicative situations among collaborating students or between teachers and students. In this situation, researchers who attempt to understand the learning processes from their own observational descriptions of the events, analogies, students and teachers take a meta-perspective.

There are, then, three functions of analogy use that have to be clearly differentiated. First, there is the *educational* function when a teacher or textbook provides a post-festum analogy with a certain educational intention. Second, there is the *heuristic* function when the learner attempts to make use of an analogy provided. Third, there is the *explicative* function when researchers analyze the interplay of educational and heuristic functions from their meta-level perspective. Here the analogy is used as an explicative tool to understand learning processes and the role of the analogy in this learning process.

1.5. Purpose of the study

This study is part of a larger research agenda concerning the role of analogies in learning, and particularly in conceptual change. The present investigation was designed to provide a better understanding of the micro-processes of conceptual change that is brought about by teacher-provided and self-generated analogies. This study contextualizes conceptual change in a sociocultural matrix by drawing on the theoretical frameworks of conceptual change and discourse analysis.

2. Method

2.1. *Research design*

This study was designed as an exploratory investigation on the role of analogies in conceptual change and is part of an ongoing research program on developing new theoretical models of learning science by means of analogies. With respect to physics content, the study is based on the notion of “educational reconstruction” (Kattmann, Duit, Gropengießer, & Komorek, 1996; Duit, Komorek, & Wilbers, 1997). Educational reconstruction aims at investigating whether specific subject matter is accessible to students and worthwhile teaching. In the present study, the subject matter domain was the physics of non-linear systems. Consistent with its exploratory theory-building nature, the study employs qualitative educational research methods (Erickson, 1986; Flick, Kardoff, Keupp, Rosenstiel, & Wolff, 1991; Guba & Lincoln, 1989). With respect to the use of discourse and interaction analysis, we draw on the methods developed in our earlier research of this kind (Roth, 1995a,b). Our interpretations are based on the above distinction between educational, heuristic and explicative functions of analogies. Verbal and non-verbal actions and interactions among students and between students and teacher are the units of analysis.

2.2. *Participants*

The instructional module on non-linear physics outlined below was taught in an academically streamed grade 10 class of a German Grammar school. There were 25 students (16 female and 9 male students). One of the authors (Komorek) taught this unit. He had previously taught a similar unit, but included much more group work and interactions between students for the purposes of the present study. To allow students freedom in developing their own analogies, he deliberately restricted his guidance.

2.3. *Instructional module on limited predictability of chaotic systems*

This unit emerged from an ongoing research project on investigating students’ learning of core ideas in chaos theory (Duit & Komorek, 1997). In this unit, the magnetic pendulum (Fig. 2) is used as a paradigm case of chaotic systems. Three magnets (all poles point to the same direction) are arranged symmetrically so that the iron bob moves in a combined magnetic and gravitational field. The locus of force equilibrium between pairs of adjacent magnets forms a star shape which leads to the emergence of the descriptor “Mercedes star” used by all members of the classroom community. The non-linearities of the magnetic pendulum are caused along the star-shaped locus of force equilibrium. Minute disturbances of the pendulum bob along its trajectory (including the starting point) can lead to considerable deviations, especially after the bob passed repeatedly the points of force equilibrium. As a consequence the motion of the pendulum bob may not be predicted for a longer period of time.

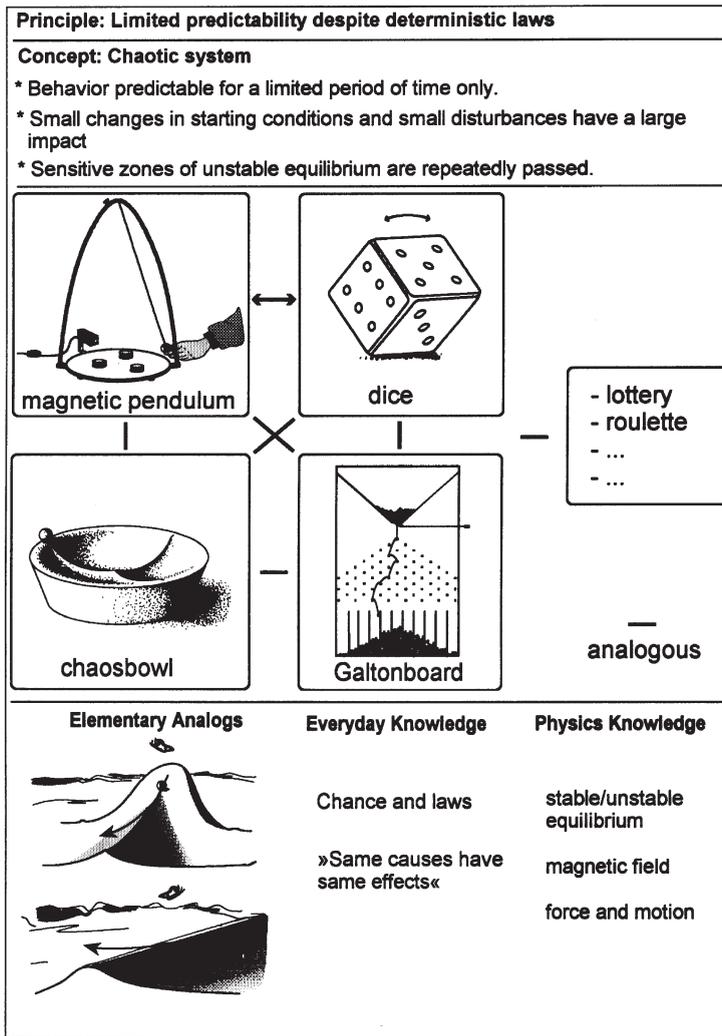


Fig. 2. On the structure of the module on chaotic systems.

This unit was taught in four 90-minute lessons spread over a 2-week period. A whole-class discussion, during which results were communicated, summarized, and implications drawn, followed each student activity.

- The unit began with the teacher presenting the pendulum to the students and asking for predictions of the path the pendulum bob takes. After the experiment was completed, the students commented on its (unexpected) outcome. The teacher asked for predictions as to whether or not the path the pendulum takes will be the same in another trial. After several investigations of this kind, students were

given time to find out in group work whether there are certain patterns concerning the target magnet. As a final activity of the first lesson, students studied the structure of the magnetic field.

- During the second lesson, students were asked to construct an explanation for the chaotic behavior—that is, on the basis of their observational sentences, they were now asked to construct theoretical sentences. Working in groups of four, they were initially told that the adequate explanation refers to the lines of equal forces to the right and left magnet. After about 15 minutes, the teacher provided each group with drawings (ridge and wall, Fig. 2) that, from a scientific perspective, have analogical relations with the chaos pendulum. The teacher hinted that these drawings might help the students to understand chaotic behavior. Fifteen minutes later, he supplied students with the chaos bowl (Fig. 2), another artifact that has analogical relations with the chaos pendulum. No further information and support were provided, as we wanted to investigate students' attempts in constructing analogical relations with the target situation (chaos pendulum).
- Students spent the entire third lesson investigating an ideal model of the chaos pendulum. This ideal model was implemented by means of a computer simulation that allowed students to explore the impact of small changes of the starting point or small stochastic influences on the trajectory of the simulated bob. The superposition of consecutive runs afforded direct comparisons of specific influences on the trajectories. This activity helps students to recognize that the chaotic pendulum is a deterministic system to which limited predictability is introduced in the form of stochastic noise (which can be eliminated in the simulation).
- During the fourth lesson, students discussed and conceptualized chaotic systems of their own design. Each student group was asked to provide (a) a description of their system's behavior and (b) a description of the critical aspects that make the system a chaotic one.

Analogies then play a key role in our module, helping students to understand the chaotic behavior of the magnetic pendulum. Here, analogies were used that draw upon situations that should be familiar to students from everyday experiences ("elementary analogies", Fig. 2). Analogical relations between different chaotic systems investigated in the unit were employed to pin down common features of all chaotic systems (i.e. possessing sensitive zones of unstable equilibrium), comprising the abstract concept of "chaotic systems". The unit aims to guide students to understand that there might even be simple systems that might not be predicted for a longer period of time.

2.4. *Data sources*

Several data sources were used to assess students' understandings of chaotic systems and study their interactions and sense-making during the lessons. Prior to the unit, students were asked to answer a series of questions designed to elicit their pre-instructional ideas on causality and predictability of processes. Three groups of students (13 of the 25 students) were videotaped throughout the eight-lesson unit. Dur-

ing whole-class discussions, two cameras were used to triangulate the speakers to record all utterances with maximum reliability. In addition to the videotapes, between two and four researchers made fieldnotes of the classroom events; these notes were transcribed and entered our database. Interviews with 12 students and students' notebook entries during the unit completed the data corpus. The students we videotaped and interviewed represented the class in terms of achievement and gender distribution. We videotaped one male group (4 Ss), one female group (5 Ss), and one mixed group (2 females, 3 males). For the interviews which were conducted one week after completion of the unit, we selected 8 of the students from the videotaped groups, and 4 others who were willing and able to express their views and understandings on the topic (7 females, 5 males). The interviews were semi-structured. They were structured in that all interviewers followed the same topics, covering the chaotic systems from the unit and an additional one that they had not seen in class (protocols are available from the authors). They were open in so far as they allowed interviewer and interviewee to explore relevant issues in depth without an a priori structure. (The interview schedule and initial questionnaire were based on the results of earlier pilot studies by Duit and Komorek, 1997; these are available from the authors upon request.)

2.5. *Data analysis*

The authors met for daily discussions and interpretations of issues that arose during the data collection and transcription of the videotaped lesson and audiotaped interviews (transcriptions were completed by the authors). We began by reading and annotating all transcriptions independently and subsequently met for discussions and joint analysis. We recorded our meetings in field notes that also entered our database. From these meetings emerged initial assertions about student learning and learning processes which we tested in the entire database. We arrived at the assertions stated below through repeated cycles of testing and refining (or abandoning) hypotheses.

3. Findings

Two pilot studies (Duit & Komorek, 1997) revealed that analogies can be powerful tools in guiding students towards an understanding of limited predictability of chaotic systems. Students used analogies to reconstruct insights even 10 months after participating in a pilot version of the present instructional module. With respect to the present study, two points deserve highlighting. First, the construction of canonical analogies was facilitated by surface similarities (such as geometrical resemblance) that led many students to construct deep structures as predicted by Gentner and Landers (1985). Second, there was convincing support for the hypothesis that understandings of the base and target are constructed in a mutually constitutive fashion.

The present study was designed to provide micro-level descriptions of the affordances and constraints of analogies during a unit on chaos theory. Before presenting these descriptions, we summarize our findings with respect to students' learning and

the role of the post-festum analogies in the form of eight assertions. (We provided detailed evidence for these assertions elsewhere: see Duit, Komorek, Wilbers, & Roth, 1999.)

3.1. *Summary of results*

In general, this study confirmed the results of our pilot studies. The following assertions summarize our findings:

1. Students generated only a small number of spontaneous comparisons with familiar phenomena to explain the behavior of the magnetic pendulum. Most of the comparisons are based on surface-level associations.
2. The “elementary analogies” (wall and ridge) assist some students in spontaneously constructing an understanding of the magnetic pendulum’s chaotic behavior. Providing additional support for constructing appropriate observation sentences of base and target that allow a mapping of the key features can increase the proportion of students who construct analogical relations.
3. Students’ small-group interactions during which they can discuss and negotiate initial observation sentences appear to support the construction of canonical observational descriptions and, hence, the desired analogies.
4. The parallel construction of relevant observational descriptions (i.e. those that bring to the foreground canonical aspects and deep structures) of the base and target phenomena usually does not occur spontaneously. However, given sufficient small-group discussion time and specific hints, many students do construct the desired analogy.
5. The chaos bowl (Fig. 2) generally constituted the most fruitful base phenomenon for understanding the magnetic pendulum (target). However, even in this situation, all groups required substantial discussion time and teacher hints to arrive at appropriate observation sentences and construct the desired analogical relations.
6. In the case of the chaos bowl, surface similarities (chaos bowl and magnetic pendulum both have the “Mercedes-Benz star” and hence share similarities of geometrical appearance) appear to support the initial construction of analogical relations and the subsequent construction of deep structure similarities. In this, the present study confirms the predictions of the analogical mapping theory (Gentner & Landers, 1985). However, there is also evidence in our data corpus that recognizing the similarity of geometrical appearance does not lead to an understanding of deep structure similarities. Some students, for instance, sought to generalize the descriptor “Mercedes star” to all observation sentences and therefore either (a) did not recognize chaotic systems in which the locus of non-linearities was not star-shaped or (b) inappropriately identified systems as chaotic systems because they described a star-shaped feature.
7. In many situations, we observed students frequently switching perspectives: students viewed the target from the perspective of the base and viewed the base from the perspective of the target. That is, students tested conjectures, based on observational sentences about one system, in the other system. In all of the groups

we observed, students made use of the symmetrical nature of the analogical relation without being guided to this possibility by the teacher.

8. As expected, students elaborated their understanding of the central feature of chaotic systems—the “sensitive” zones or locus of unstable equilibria—based on the symmetry of the analogical relation.

3.2. *Analogies and conceptual change: between Scylla and Charybdis*

The theoretical and methodological setting of the present study allowed us to construct a fine-grained picture of analogy use, that is, a micro-level description of the role of analogies in learning about chaos theory. It has been shown that decoding of analogies provided by the teacher and the mapping processes analyzed from the perspective of the microstructure of verbal and non-verbal actions and interactions are most complex.

3.2.1. *The role of observation sentences*

There is considerable evidence in our data that observational sentences are crucial in students’ learning processes. Similarity of observation sentences about two situations (base and target) frequently encourages the construction of analogical relations, both appropriate and inappropriate from a canonical perspective. On the other hand, different observation sentences impede the construction of analogical relations even if, from a canonical perspective, two situations can be treated as analogies of each other. For example, Lars provided an observational description that appears to exclude the possibility of theoretical sentences that frame the phenomena in terms of small influences and their impact at the path of chaotic systems:

These small ever-changing effects, like wind now or air movements, do not act much on the ball. They can’t. And still less when it has a lot of momentum then there is even less. (Lars)

Traces of this understanding become evident in our interviews when several students seem to intimate that the small influences are only effective when they occur exactly when the pendulum bob is in an unstable equilibrium.

When the pendulum is inside the magnetic field, it is not susceptible to, how shall I say, by a slight air movement, because it is so heavy . . . But when it is where the forces cancel, then it can really be influenced easily. (Janina)

Katrin and her group mates came to describe the chaos pendulum in the same way as a Foucault pendulum that they had seen in a science museum (see below for more details). However, whereas the motion of the magnetic pendulum is subject to unpredictability due to sensitive zones passed several times in the magnetic-cum-gravitational potential, Foucault’s pendulum is predictable and appears to change its plane of swing during the day because of the earth’s rotation. From a canonical

physics perspective, the students' analogy is incorrect. This description began with the observational sentence that the magnetic pendulum veered off its plan of motion because "it cannot move on an infinitely narrow line, it cannot remain on the edge" (Aleks). This observational sentence also fits the Foucault pendulum, which Janina had brought up by association. Their self-generated analogy was based on the similarity of the observation sentences for the magnetic pendulum and Foucault's pendulum. From an observer's perspective, these students' problem arose from the fact that they did not test their analogy as to how far it would explain the target phenomenon, the magnetic pendulum and its chaotic movement.

Throughout our data sources, we found observational descriptions that, at a minimum, appear to impede the successful construction of a canonical analogy. The butterflies in the drawings were interpreted as indicators of wind direction, "harmony in chaos", and images from the practice of psychiatrists (ink blots); other students suggested that they were irrelevant. Katrin and Aleks both suggested that they might represent a small air movement that influences the motion of the ball, but then discarded this description as something to laugh at.

In the other direction, it appeared to be important for the construction of the analogy that students' observational sentences included descriptions of the points of instability in the case of the magnetic pendulum (on the Mercedes star), the ridges in the drawings, and the ridges in the chaos bowl. For example, Chris described the situation of the steel ball on a ridge in the chaos bowl as "and here it is labile, then it rolls either here [left] or there [right] or there [straight]." He used a semantically equivalent description of the pendulum a few utterances later: "Yes, on the Mercedes star, it is also labile." Here, the same descriptions of stable and unstable equilibrium, the points where the net forces are zero (at least those from neighboring magnets), were used for the chaos bowl and magnet pendulum. Points of stability were recognized in the final position near a magnet for the pendulum. Lars referred to an earlier conversation in which they discussed what happens to the pendulum exactly between two magnets; here they had recognized that the net force is zero so that the gravitational force could pull it towards the middle.

Students constructed spontaneous comparisons from observational descriptions, which helped in some situations (to understand the notions of stable, labile, and indifferent) whereas these descriptions led them into inappropriate directions in other situations. During group work, Katrin and her peers described the balls in the drawings as moving left, right, or straight on the edge. Katrin used this description to construct a new, but inappropriate, chaotic system:

Like an atomic test, the chain reaction. I mean, there you have the nuclei that split and then fly around everywhere, until they split another nucleus so that they can be influenced in their direction of flight. (Katrin)

3.2.2. *The symmetry of the analogical relations employed*

Our data suggest that observation sentences can both hamper learning and lead to deeper understanding. For example, the description the "Mercedes star" became a

familiar way to describe the locus of non-linearities in the magnetic pendulum and chaos bowls. However, there were some situations in which this description hampered the construction of analogical relations but there were also situations in which students developed a sound basis for understanding. The following example from one student's interview shows this ambivalent role of an observation to understanding chaotic systems. The following data also underscore the role of analogies in reconstructing understanding. The switch of perspectives facilitated by the symmetrical nature of the analogy relation obviously helped the student, Kirstin, to develop an understanding of what chaotic systems have in common.

Without major difficulties, Kirstin described the wall and ridge analogies provided by the interviewer. But Kirstin's problem was that she could not initially find a "Mercedes star" in the drawing of the ridge. After a short while she pointed to the ridge with her finger, moved the finger along the ridge and then completed the figure of the Mercedes star by pointing to the two lines into which the ridge divides (Fig. 2). During instruction, one student had proposed the "Mercedes star" as a label for the key feature of all chaotic systems denoting the zones of unstable equilibrium. Whereas the ridgeline is such a zone, the other two lines that follow in the drawing are not. For Kirstin the dominating feature of the descriptor "Mercedes star" was not the "sensitive zone of unstable equilibrium" but a mere geometrical appearance. This interpretation is supported by Kirstin's apparent difficulties to explain how a dice works. Here too, she searched for something that could be described with the label "Mercedes star" (I=Interviewer; K=Kirstin; comments in brackets; figures in brackets give wait time in seconds):

I: What about the dice? You know what a dice is? You throw it, and you cannot predict which figure will come.

K: Yes (hesitant).

I: Do you know why this is the case?

K: No, but in some way for me that has nothing to do with the Mercedes star. (2) Sure, there are six permutations and then it has to decide.

I: OK, let us try not to think of the Mercedes star. Why is it not possible to predict which figure will come?

K: Well, also because of influences. And because one does not start in the same way and . . .

I: Why is this of importance?

K: Well, why not?

Although Kirstin began to reconstruct her knowledge of chaotic systems in mentioning characteristics of them besides the mere geometrical symbol Mercedes star (such as the impact of influences and the starting point), she did not explain, at this point, why the dice demonstrates stochastic behavior. But her explanation of the Galton board (Fig. 2), which was not used during instruction, provided her with insights that turned out to become a key element for constructing the features characteristic of all chaotic systems. On the Galton board, small balls are released and roll down through an arrangement of nails. Kirstin suggested that the nails are the "points

of decisions.” Very small differences in the starting position and minute disturbances of the ball’s trajectory determine whether a ball passes to the left or right of a nail.

At this stage of the interview the interviewer decided to find out whether Kirstin would employ this insight also to understand the other chaotic systems discussed previously during the interview.

I: To put it into other words, do they have something in common that causes the large impact of small disturbances and the small differences in the starting position?

K: Well, for all of them there is this decision between right and left. I do not know.

I: Here in the case of the magnetic pendulum, where is this point of decision?

K: Yeah, between the magnets.

I: And in this case (chaos bowl)?

K: On this line (points to the ridges).

I: And here (Galton board)?

K: On the nails.

I: Could you point to them also in the case of the dice?

K: Yes, the edge. Well, one could throw the dice that it comes to rest standing at an edge. Of course, that is not possible, a breath of air comes and it goes to the right and I only have the figure 1 although if it would have gone to the left there would have been the figure 6 or so.

Here, Kirstin explained the behavior of a dice although she had not done so earlier. She had reconstructed her framework of understanding. It appears that the frequent change of perspectives allowed Kirstin to work out that key characteristic of all chaotic systems to possess sensitive zones of unstable equilibrium. She could retroactively use the observational description of sensitive zones to characterize the dice as a chaotic system.

3.2.3. *The Mercedes star—both a fruitful and a misleading symbol*

In this class, the “Mercedes star” became an important part of the language about chaotic systems.² That is, students and teacher used the expression for talking about key features of chaotic systems. Rani introduced the “Mercedes star” when the teacher asked for a description of the geometrical structure of the field in which the iron bob of the magnetic pendulum moves. The word was immediately ratified by the teacher and developed as a sign that referred to the sensitive zones of unstable equilibrium characteristic of every chaotic system. A detailed analysis of video and interview transcripts of 11 students revealed that about half of them used the sign in this way. Daniela, one of these students, explained the function of the Galton board during the interview:

² In one of our pilot studies, students also generated this description. But in another study (with Helga Stadler, University of Vienna) the Mercedes star was not part of students’ language game about chaotic systems.

I: Are all balls going to the same box?

D: No. I would say, because at the nails, this is the Mercedes star again, there they have to decide, whether to go to the right or to the left.

I: Aha. Where is the Mercedes star?

D: Here, the nails, in a way.

I: That does not look like a Mercedes star!

D: Well, not in this case (laughs), but it represents the same, it does not look like a Mercedes star, but it is in this case the same.

But, as we showed above, there were also students who used the “Mercedes star” as an iconic description of chaotic systems. Janina was among the three students who were deeply misled by this symbol. While her group developed its own chaotic system (Lesson 4), Janina convinced her peers to present the following system to the class: an arrangement of domino bricks as given in Fig. 3. She explained to the class that the domino bricks formed a chaotic system because it had several Mercedes stars, namely the junctions of the rows of bricks. Here, the geometrical arrangement allows valid observation sentences including “Mercedes star.” However, from a scientific perspective, this geometric arrangement does not make the system chaotic in principle. The interview carried out with Janina one week later reveals that all of her theoretical sentences about chaotic systems included the “Mercedes star.”

When asked to explain the random behavior of the magnetic pendulum and the chaos bowl, Janina provided explanations that could be interpreted as canonical responses. Invited to explain the behavior of the dice she brings the Mercedes star into play.

I: . . . you talked about two systems, about two devices, the pendulum and then you mentioned the dice. Is there anything in case of the dice that resembles the Mercedes star?

J: I do not know, it also has such edges.

I: And what happens at these edges?

J: In principle the same, like a Mercedes star.

I: What is the same, that is what I wanted to know.

J: That, in which direction it may fall.

I: Toppling over?

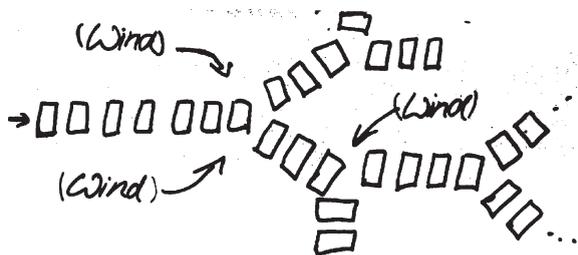


Fig. 3. Janina's “chaotic system”.

J: Yes, also that, the direction of the Mercedes star, only that it has another form here, it is not as straight, well, it is somewhat straight, but it leads more in different directions.

Here, it appears that Janina sought a geometrical arrangement to which observation sentences including Mercedes star could be applied. In the absence of such arrangements, Janina was even led to issues she seemed to have understood. For example, Janina tried to explain the behavior of the balls on the Galton board by explicitly pointing out many Mercedes stars formed by the arrangement of nails. Although the Galton board is a chaotic system, those features that Janina described as “Mercedes stars” are not those that bring about the chaotic trajectories of the balls. Taken as a whole, then, the interview with Janina highlights the presence of star-shaped geometrical features predominant in her observational and theoretical language. Janina had been led to construct a conceptual framework of a chaotic system that differed considerably from the teacher-desired canonical framework.

3.2.4. Foucault’s pendulum—how students’ sense-making attempts may lead into unintended directions

There are several cases in our data that allow a study of learning processes involving post-festum analogies. The learning processes are complex and subject to many contingencies of students’ interactions, including specific prior experiences, conversational history, and nature of artifacts at hand. Because of these contingencies, students’ work may not lead to the construction of the desired analogical relations between the various teacher-provided instructional materials. We focus on one example: the construction of a student-generated analogy (Foucault’s pendulum) by a group of four girls (for an extensive analysis of this case, see Roth & Duit, 1997).

After the four girls tried for about 15 minutes to develop an explanation of the magnetic pendulum’s chaotic behavior, the teacher handed them the drawings of wall and ridge (Fig. 2). A lengthy discussion follows in which a number of ideas introduced by single girls are not taken on board by the others. Katrin, for instance, immediately uttered the observation sentence, “I see a butterfly,” but her peers attended to other issues. They spoke about centrifugal forces acting on the moving object and the attractive forces of the magnets. They also described the fact that the ball approaching the wall in one of her drawings may topple over. Despite their success in arriving at a number of observation sentences that applied to base and target situations, the girls did not construct their explanation.

Then, all of a sudden, the girls removed one of the magnets and thereby arranged the magnetic pendulum to resemble the ridge drawing. They started the pendulum bob in such a way that it swung exactly on a line between the two magnets. The bob now moved along a ridge similar to the ball in the drawing. However, the change in the geometrical arrangement did not lead to an explanation that was pleasing to the group as a whole. They discussed, for instance, the influence of small breaths of air, but they did not understand how this impact causes the chaotic behavior of the pendulum. While three students were about to stop their investigation, Janina observed the swinging pendulum in a meditative fashion for more than a minute.

As she waited for the pendulum to come to rest, she suddenly suggested that the pendulum could never come to rest, like Foucault's pendulum. She explained to her peers that the pendulum could never come to a total rest, as the earth is rotating all the time. The swinging pendulum reminded Janina of the Foucault pendulum that was discussed in physics instruction before and that she had seen in a science museum.

In the conversation that followed, two others supported the idea whereas Kirstin remained skeptical. The argumentation in favor of Janina's initial idea was about the following: the pendulum cannot stay exactly on the line between the two magnets (the ridge) because the earth rotates all the time and, hence, the pendulum bob has to move to one magnet. Kirstin, on the other hand, suggested that the rotation of the earth would not be large enough to cause that effect. Viewed from the perspective of physics it may be surprising that none of the conversation participants realized that their theoretical sentences explained a consistent deviation to one side but not a stochastic behavior. Excited about their self-generated analogy, the women attempted to explain Foucault's pendulum to the teacher but met with a cool reception. In the end, the idea "died", not because the girls were convinced of its incorrectness but because it lacked support.³ That is, in the case of this group, the interaction of students with each other and with the instructional materials led to the momentary public construction of a conceptual framework that was later abandoned. We did not find evidence during the interview that any one of the three students interviewed actually appropriated the framework from the group situation into their individual understandings.

4. Discussion

This study concerning the role of analogies in an instructional unit on the limited predictability of chaotic systems was exploratory in nature and designed to contribute to the development of a theoretical framework for the use of analogies in science instruction. We therefore investigated microprocesses of analogical reasoning, including (a) how students constructed observational descriptions of post-festum analogies provided in the form of drawings and physical artifacts and (b) how students generated analogical relations to understand a domain so far unknown (chaotic pendulum).

On the basis of the present study, we conclude that analogies *may* in fact be powerful tools to support learning science viewed from a conceptual change perspective. But we also showed that post-festum analogies may interfere with students' learning and understanding phenomena from a canonical perspective. Our theoretical framework of analogies (Fig. 1) allows us to explain why and how the use of analogies for teaching science is a course between Scylla and Charybdis. The context of a particular analogy is different for students and teacher which leads them to

³ Readers will recognize that this is the fate of outdated paradigms (Kuhn, 1970) and language games that no longer provide sufficient observational and theoretical sentences (Rorty, 1989).

construct different observation sentences. Because analogical relations are built up on the basis of the similarity of observation sentences in two domains and because the number of observation sentences for any given phenomenon is infinite, the construction of specific analogical relations has to be seen as an accomplishment rather than an unproblematic matter of course. In this, the present investigation underscores the results of another study of learning physics from student investigations and teacher demonstrations (Roth et al., 1997a,b). In that study, not only student investigations with specific materials but also teacher demonstrations led to ranges of incompatible observation sentences that supported different theoretical sentences. Our observations also suggest that it is unlikely that different groups of students generate the same understandings about complex phenomena (i.e. formulate theoretical sentences) as they start from different contexts. We therefore conclude that teaching strategies have to develop both analogical relations *and* context into the desired direction. This may require substantial teacher guidance.

The inclusion of a discourse analysis perspective allows us to understand students in developing desired analogical relations by revealing the microstructure of conversations. This perspective on analogies allows us, for instance, to frame affordances and constraints of learning science by means of analogies. First, observation sentences allow students to use discourse that is grounded in their everyday experiences of the physical world to describe phenomena which are not directly accessible or described by notions in canonical physics not referring to direct experience. This holds, for example, for the chaos bowl that is a physical analogy of the magnetic-cum-gravitational potential to the chaos pendulum. On the other hand, students' observation sentences, if they do not describe those aspects central to a scientific understanding of the base phenomenon, may actually constrain the construction of learning-enhancing analogies.

We found that students tended to utter observation sentences for both base and target phenomena. However, we observed few occasions where students attempted to generate and test analogical relations between base and target phenomena on their own. A substantial number of the comparisons made were based on observation sentences of surface-level aspects. For example, when students initially investigated the behavior of the magnetic pendulum, many groups soon characterized it as stochastic. They quickly associated this behavior with the familiar cases of playing roulette and lotto or rolling dice. There were few attempts within any group (including the three that were not filmed) to develop the stated similarities into a full analogy and test its fruitfulness. In fact, only one student (Christoph) developed analogical relations between a pencil in labile and stable positions and similar labile and stable positions of the pendulum bob on the Mercedes star, the steel ball on the ridges in the chaos bowl, and the balls on the ridges in the drawings.

Our study is grounded in constructivist epistemology, bringing together conceptual change and sociocultural perspectives, which leads to an inclusive perspective of conceptual change (e.g. Duit & Treagust, 1998). This integrated approach allows us to investigate issues at the level of the classroom that were traditionally studied at the level of the individual. In this way, we address some of the criticisms leveled in the past against conceptual change approaches. Our modified conceptual change

position includes, for instance, social aspects of knowledge construction that were developed within social constructivism. Our notion of conceptual change also includes the possibility of “learning pathways” (Scott, 1992), along which students progress from their pre-instructional conceptions to canonical conceptions (which researchers recognize from the different theoretical sentences students produce). We then focus on the potential of specific post-festum analogies to scaffold successful learning pathways. We do so by reconstructing the perspectives of learners *and* teachers (or, more generally, providers of a post-festum analogy). Our empirical approach also focuses on knowledge construction within communities of learners by analyzing students’ discourse in small-group and whole-class situations. This study shows that the two perspectives allow complementary views on analogical reasoning and thereby avoids the one-sidedness of single-perspective approaches.

From an educational point of view the approach of open inquiry has proven problematic in a situation where specific, canonical analogical relations were to be developed. In this study, students were deliberately given little guidance in describing the different artifacts and events and in mapping different phenomena onto each other. All groups experienced some difficulty with this openness—which may have arisen in part from the unfamiliar teaching strategy that contrasted with students’ familiar physics lectures. Students did not automatically construct canonical understandings of the magnetic pendulum despite the carefully constructed and tested post-festum analogies. Our observations are therefore congruent with the contention that substantial guidance seems to be necessary if teachers want their students to construct specific analogies and understandings that are pleasing to both students and teacher (e.g. Metz, 1995).

5. Outlook

This study is part of an ongoing project concerned with investigating the micro-structure of analogical reasoning in science classrooms and developing a theoretical framework for instructional strategies based on post-festum analogies. At present, several follow-up studies draw on the findings presented here. First, Duit (in collaboration with Helga Stadler, University of Vienna) replicated the present study but provided students with much more guidance than was provided in the present study. A first, cursory analysis of the data revealed support for the findings presented here. Furthermore, the preliminary data analysis suggests that students’ analogical reasoning processes received substantial support by the guidance provided. A second study uses the same post-festum analogies but employs the methodology of “teaching experiment” (Steffe & D’Ambrosio, 1996) which allows greater teacher control of the instructional progress. The teaching experiment merges open-inquiry sessions of groups of students and critical interviews that were conducted consecutively in the present study. The interviewer/instructor guides groups of four students as they deal with the topics of non-linear physics. The results of this study fully support the findings presented here. The teaching experiment design, however, allowed more fine-grained analyses that were used to develop a model of heuristic analogies (Wilbers, 2000; for a brief summary of findings, see Wilbers & Duit, 2000).

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