Effect of Knowledge Integration Activities on Students' Perception of the Earth's Crust as a Cyclic System

Yael Kali,[1] Nir Orion,[2] Bat-Sheva Eylon[2]

[1]*The Department of Education in Technology and Science, Technion–Israel Institute of Technology, Haifa 32000, Israel*

[2]*Science Teaching Department, Weizmann Institute of Science, Rehovot, Israel*

Received 19 September 2002; Accepted 3 January 2003

Abstract: Systems thinking is regarded as a high-order thinking skill required in scientific, technological, and everyday domains. However, little is known about systems thinking in the context of science education. In the current research, students' understanding of the rock cycle system after a learning program was characterized, and the effect of a concluding knowledge integration activity on their systems thinking was studied. Answers to an open-ended test were interpreted using a systems thinking continuum, ranging from a completely static view of the system to an understanding of the system's cyclic nature. A meaningful improvement in students' views of the rock cycle toward the higher side of the systems thinking continuum was found after the knowledge integration activity. Students became more aware of the dynamic and cyclic nature of the rock cycle, and their ability to construct sequences of processes representing material transformation in relatively large chunks significantly improved. Success of the knowledge integration activity stresses the importance of postknowledge acquisition activities, which engage students in a dual process of differentiation of their knowledge and reintegration in a systems context. We suggest including such activities in curricula involving systems-based contents, particularly in earth science, in which systems thinking can bring about environmental literacy. © 2003 Wiley Periodicals, Inc. J Res Sci Teach 40: 545–565, 2003

Current earth science education is characterized by a shift toward a systems approach to teaching and curriculum development (Mayer, 2002). Earth science educators call for reexamining the teaching and learning of traditional earth science in the context of many environmental and social issues facing the planet (Fortner & Mayer, 1998). Orion (1998) claimed that systems thinking about the different earth systems, i.e., the geosphere, hydrosphere, atmosphere and biosphere (including humanity), is fundamental to environmental literacy. He emphasized that understanding the reciprocal relationships within and between each of these systems is necessary for informed decision making concerning environmental issues.

Correspondence to: Y. Kali; E-mail: yaelkal@yahoo.com
DOI 10.1002/tea.10096
Published online in Wiley InterScience (www.interscience.wiley.com).

According to this approach, a new earth sciences curriculum for the Israeli junior high schools was developed, emphasizing each of the earth's systems in different grade levels, starting with the geosphere. The rock cycle is a 40-hour learning program which initiates this curriculum in the seventh grade. One challenge in the development of this program was to assist students in understanding the rock cycle as a system rather than a set of facts about the earth's crust (Kali, 2000).

Systems thinking has been extensively studied in many domains such as social sciences (e.g., Senge, 1998), medicine (e.g., Faughnan & Elson, 1998), psychology (e.g., Emery, 1992), curriculum development (e.g., Dror, 1984), decision making (e.g., Graczyk, 1993), project management (e.g., Lewis, 1998), engineering (e.g., Fordyce, 1988) and mathematics (e.g., Ossimitz, 2000). However, little is known about systems thinking in the context of science education.

The rock cycle is a system including the crust of the earth, which is characterized by a cyclic and dynamic nature. The rocks exposed on the surface of the earth are only a small sample in time and space of constant material transformation within the crust, driven by geological processes (e.g., weathering, sedimentation, burial, metamorphism, melting, crystallization of molten rocks, uplift and erosion) (Figure 1). The rock cycle can be viewed as a closed system because hardly any material was added or removed from this system in the time involved in

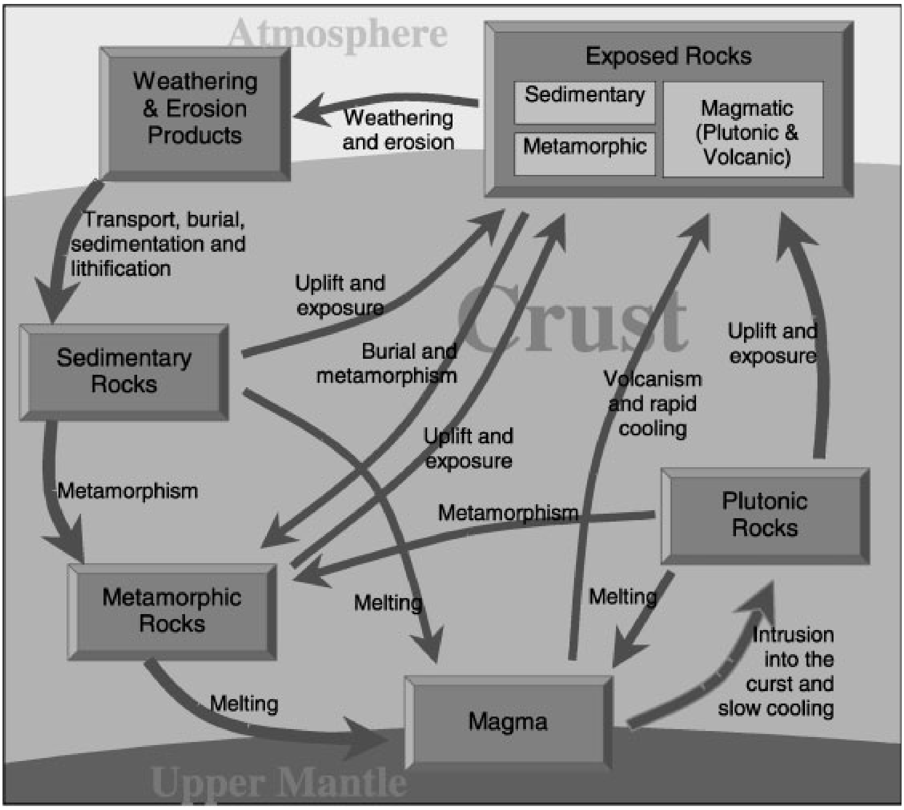


Figure 1. Representation of rock cycle.

students' observations. In addition, because the size of the reservoirs of this system was almost constant over this time scale, it can also be viewed as a system maintaining a dynamic equilibrium.

In the current study, understanding of the rock cycle is considered to be the ability to reconstruct long causal relationship sequences of processes and products that explain the formation of various materials of the earth. For example, an explanation of the formation of granite, which represents an understanding of the cyclic and dynamic aspects of the rock cycle, could include the following sequence of causal relationships: "The large crystals of the granite indicate that it has been created in a process of very slow cooling of magma, which occurs inside the crust. The magma was created by melting of rocks. For rocks to melt, they had to go through tectonic processes that brought them into deeper areas in the earth's crust in which pressure and temperature are higher...." Because the earth's crust is a cyclic system, this retrospective construction of sequences of processes could continue endlessly. Ault (1998) referred to the occupation with conclusions about past events as retrodiction (as opposed to prediction), and claimed that its main challenge is "to hypothesize an arrangement by stages for what is observed" (p. 196). We claim that understanding the rock cycle is exactly such a challenge. We also claim that such a challenge requires systems-thinking.

To analyze the skills required to understand the rock cycle, we will focus on two definitions for systems thinking, which stem from different research areas. O'Connor and McDermott (1997), who studied economic systems, defined a system as an entity that maintains its existence and functions as a whole through the interaction of its parts. According to them, systems thinking looks at the whole, and the parts and the connections between them. Ossimitz (2000), in the mathematics area, went further to define a framework of systems thinking including four essential dimensions. "Thinking in models" is his first dimension, which involves the ability of understanding models that represent systems, as well as the ability to build such models. His second dimension is "closed loop thinking", which is a nonlinear type of thinking that takes into account interrelated structures and feedback loops between structure components. The third dimension is "dynamic thinking," which includes a retrospective view of past developments as well as foreseeing possible future trends. "Steering a system" is the fourth dimension of systems thinking, which refers to the ability to make informative actions in a system. In light of these definitions, systems thinking can be viewed as a high-order thinking skill, as it requires the ability to break down a complex topic into its constituent parts, and to put together elements to form a whole. Such skills are classified in Bloom's taxonomy as belonging to the "analysis" and the "synthesis" higher-order cognitive levels (Bloom, 1984).

Understanding the rock cycle, as defined above, can be characterized according to the definition of Ossimitz (2000), as requiring the closed loop thinking and dynamic thinking dimensions. It requires nonlinear type of thinking because it deals with construction of sequences of processes in a cyclic system, which includes several subcycles. For example, magma can be formed by melting different types of rock (see the three arrows pointing to "Magma" in Figure 1). A construction of the sequence of processes that created a specific magma would have to take into account the composition of the magma to hypothesize about possible sources or mixture of sources that created it. Such a retrospective construction, which refers to several components of a system that affect another component in an interrelated structure, represents nonlinear closed loop thinking. Because this process requires organizing past events on a time scale and understanding the consequences of different sequencing on the dynamics of the system, it also represents Ossimitz's (2000) dynamic thinking dimension.

The type of thinking required to understand the rock cycle also corresponds to the definition of systems thinking described by O'Connor and McDermott (1997). Their definition includes three levels: (a) understanding the parts of a system, (b) understanding the connections among these parts, and (c) understanding the system as a whole. We claim that to understand the rock cycle in a systems perspective, i.e., be able to construct sequences of processes within the rock cycle as described above, students must acquire understanding of the system on these three levels. The first level, understanding the parts of the rock cycle system, corresponds to a stage in which students acquire knowledge about various materials forming the earth's crust (e.g., different types of rocks, magma, weathering products) as well as the geological processes producing them (e.g., sedimentary, metamorphic, magmatic processes). The second level, understanding connections among parts of the system, involves understanding causal relationships among specific processes and their input and output products: for instance, understanding that if a magmatic rock includes very small crystals, it must have been formed in a process of rapid cooling and crystallization, which is expected to occur in a volcanic eruption. The third level, understanding the rock cycle system as a whole, involves the understanding that each output product of one process may serve as the input product for another, and that in this manner the materials of the crust are recycled through endless chains of processes and products.

Characterizing the skills required to understand the rock cycle as systems thinking skills does not provide much information about how to design curriculum materials that foster such thinking. In fact, little is known about ways to assist students in developing systems thinking. It has even been postulated that systems thinking might be an innate ability (Gudovich, 1997). However, a research area which studies similar thinking processes and deals with connections among knowledge components is the area of knowledge integration.

A considerable amount of research has characterized students' tendency to compartmentalize knowledge (e.g., Bagno & Eylon, 1997; Linn & Hsi, 2000; Lewis, 1991; Linn, Songer, & Eylon, 1996; Songer & Linn, 1991). One of the methods for dealing with this tendency is the usage of knowledge integration activities. Linn et al. (1996), for example, described the use of integration aids such as: (a) compact summaries with hierarchical maps for each topic, (b) exercises requiring students to construct and use maps, (c) explicit links among phenomenological and explanatory models, and (d) emphasis on relationships between the maps for each topic. Songer and Linn (1991) used other integration aids such as pragmatic principles (abstract qualitative rules) and prototypic events (familiar situations illustrating scientific phenomena). They concluded that "Students rarely spontaneously integrate information presented in isolation," and that "In order for students to move beyond isolated ideas and into a more predictive and productive understanding of science, intervention is needed" (p. 781). Linn and Hsi (2000) described a pedagogical framework, called the Scaffolded Knowledge Integration, for designing effective curricula for complex topics. This framework is based on the idea that the learner possesses a repertoire of models for understanding complex phenomena, and describes ways to encourage students to integrate new models with their existing perspectives. This framework was successfully used in various curricula and settings, and led to impressive improvements in student achievements (e.g., Shear, 1998).

Based on such research, we hypothesized that knowledge integration activities that were effective in assisting students in understanding complex scientific domains might also be effective in developing systems thinking in the context of the rock cycle.

Purpose

The purpose of the present study was to explore and design new activities in an existing learning program about the rock cycle, which were aimed at assisting students in gaining systems thinking in this context.

Specific objectives were the following: (a) to characterize student perception of the rock cycle system (b) to examine whether knowledge integration activities can assist students in understanding the dynamic and cyclic nature of this system; (c) to explore the effect of different versions of a knowledge integration activity on student perception of the rock cycle, (d) to evaluate this effect in terms of systems thinking, and (e) to suggest a general framework for analyzing student systems thinking.

The Iterative Design Process

The rock cycle learning program was developed in several stages. Evaluation of the first version of the program revealed that many students understood the geological processes and their products but lacked the dynamic and cyclic aspects of the crust system. In other words, they did not acquire systems thinking in this context (Kali, 2000).

After 4 years of intensive experience with students and successive formative evaluation cycles, we hypothesized that appropriate knowledge integration activities could allow students to grasp the systems view of the rock cycle. Therefore, many changes were made in the activities, aimed at assisting students in making connections between the different processes, and between each one and its input and output products (Kali, 2000). The final version of the program included three types of activities aimed at fostering such connections. Following is a description of these activities.

Inquiry of Geological Processes

Twelve guided inquiry activities for learning about each geological process are included in the program. These inquiries, in which groups of 3 or 4 students discover the geological processes, emphasize the relationships between processes and their input and output products.

Construction of Rock Cycle Activity

In this activity, students are presented with a diagram similar to the one presented in Figure 1, but without the arrows that represent geological processes. After each inquiry activity students are required to add arrows to the diagram, representing geological processes. Eventually, when the diagram is completed with all the appropriate arrows, it represents the dynamics of material transformation in the rock cycle.

Field Trip

A whole-day field trip, based on the model developed by Orion (1993), in which the knowledge acquired earlier in the lab is used for solving problems that can be explained only in the field. For instance, in the classroom, students are engaged in an inquiry activity that models the effect of transportation of pebbles in a river on the pebbles' shape and size. In the field trip, students use this knowledge to hypothesize about different sources of various pebbles they find in a creek. Students check their hypotheses soon after by examining the rocks at different locations at the river's watershed.

Despite these knowledge integration activities, the dynamic and cyclic aspects of the system were still not understood by most of the students (Kali, 2000). For instance, many students had difficulty in understanding the causal relationships that explain similarities between the characteristic of a quartz crystal inside a granite rock and a quartz grain in sandstone. Only few students were able to present a sequence of several geologic processes that tie the formation of sandstone with a granite resource. Consequently, we decided to add an intensive concluding knowledge integration activity to the learning program. This activity was aimed at assisting students in organizing all the knowledge that they had already gained, and integrating it in a dynamic and cyclic context. The current study focuses on the effect of this activity. A first version of the activity was tested in a pilot study with 37 eighth-grade students. Qualitative data including observations and video and audio recordings of student work were collected and analyzed. These data served as a basis for operative conclusions and major revisions in the design of the activity for the main study. The main study was conducted with 40 seventh-grade students from a different school and followed the pilot study with a time gap of 2 months (Figure 2). Following is a description of the activities, teaching methods, and their evolution after the conclusions of the pilot study.

Learning Materials and Teaching Methods in Pilot Study

The learning tool used in the pilot study was the software KnoW (Svivot, Inc., Israel). This PC application was designed to assist students in organizing information and constructing their knowledge. It is an open tool with a dual interface consisting of a map and a resource environment. The map enables students to construct a network of their ideas, which appear as rectangles connected by arrows (Figure 3a). The rectangles in the map represent multimedia objects (texts, images, video clips, animation, and sounds) of the resource environment, and the arrows represent hyperlinks between these resources (Figure 3b). The two environments are interconnected and editable. Consequently, changes in the map are automatically updated in the resource environment, and vice versa.

Using the software, to which the students had prior exposure in other contexts, students were asked to represent all the geological processes that produce a specific rock. All the content knowledge needed to complete the task was familiar to the students from learning the rock cycle program. Moreover, the sequence of processes they had to reconstruct was partially dealt with during the field trip. The activity lasted 10 hours and was implemented twice, each time with half

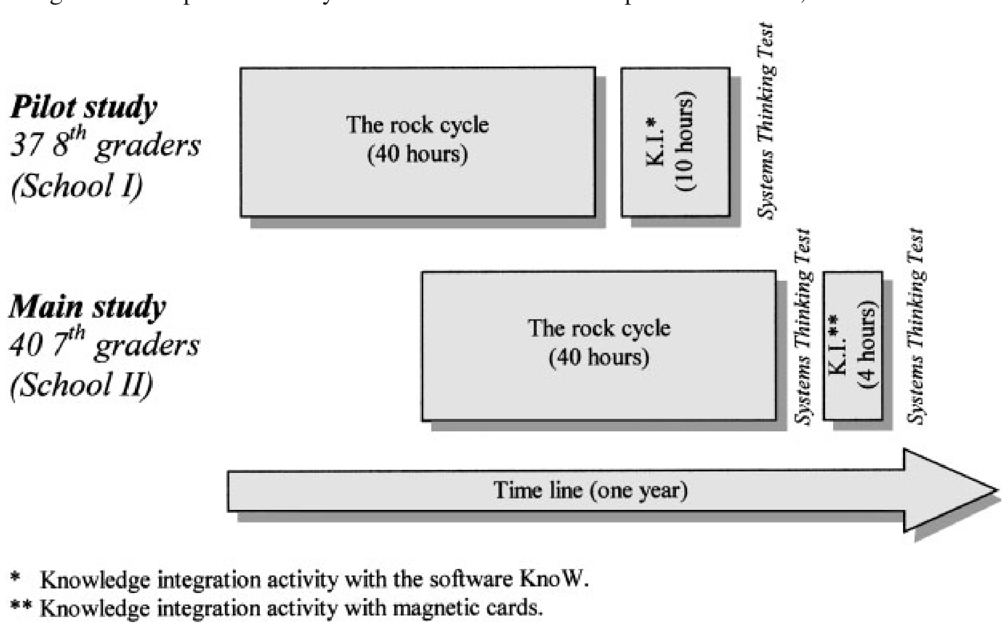


Figure 2. Timeline of the pilot and main study.

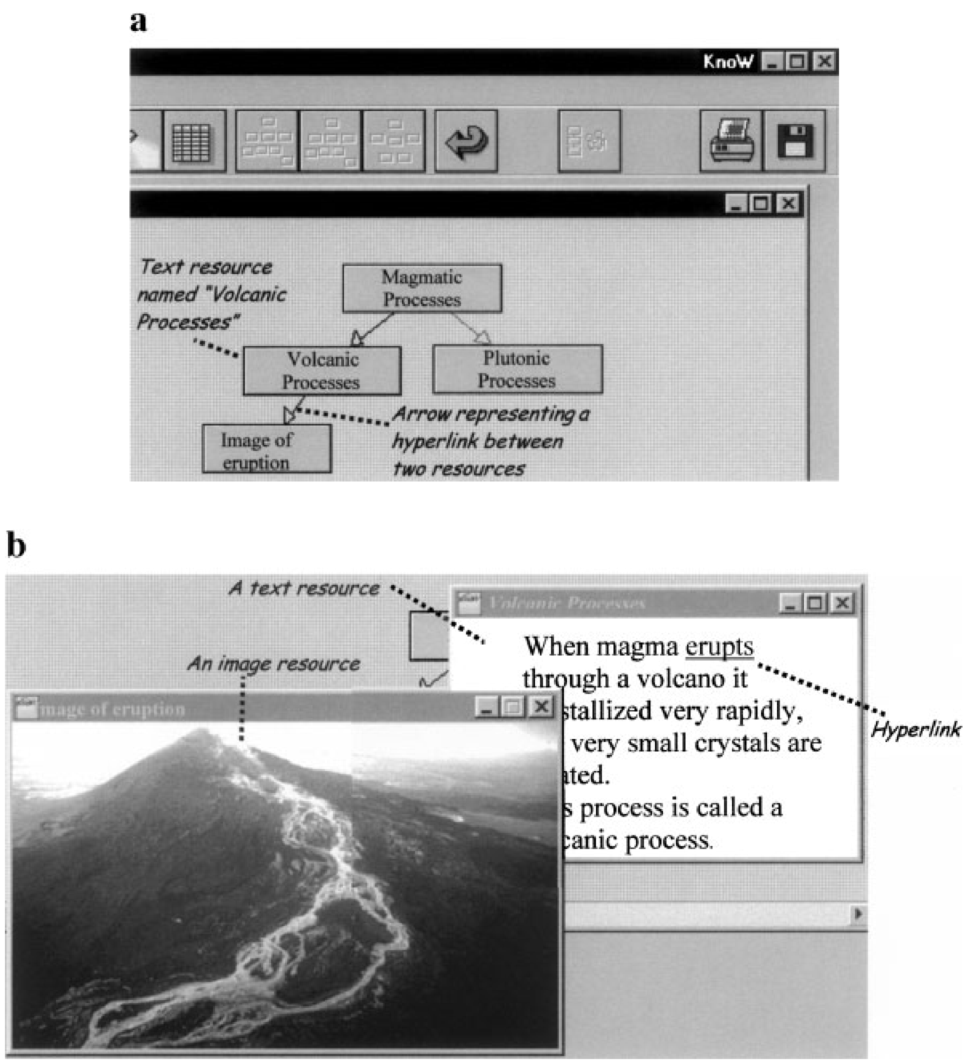
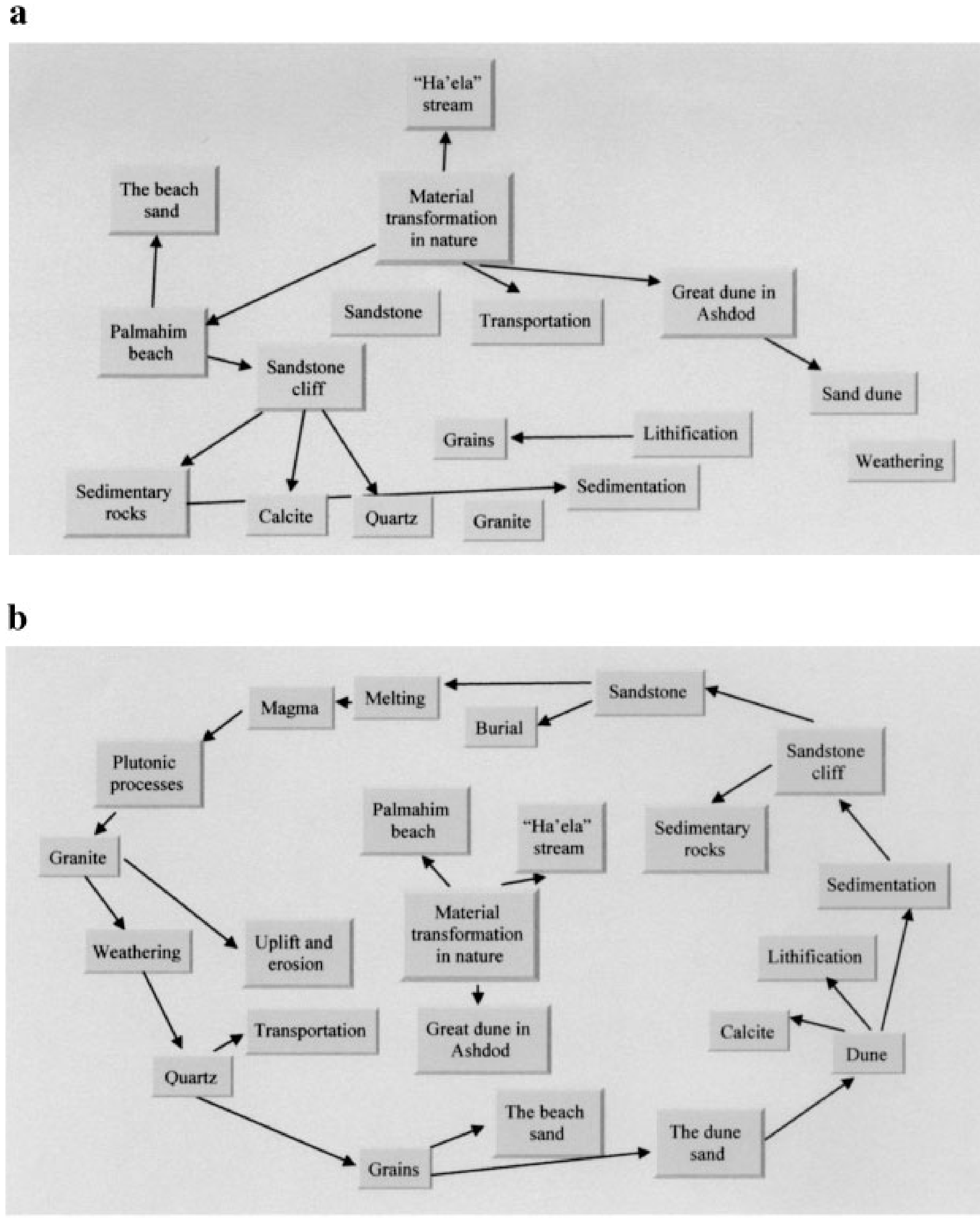


Figure 3. Interface of KnoW software. (a) Map environment. (b) Resources environment.

the class (18 and 19 students). Students worked collaboratively in groups of 3 or 4 students; the teacher was guided to serve as facilitator. The teacher's role included asking guiding questions and referring to knowledge already held by the students, rather than providing answers (Kali, 2000). Videotapes of students working on the assignment were recorded in about half the groups in each session. All the students' KnoW projects were collected, including intermediate versions saved by students during the activity.

Operative Conclusions Following the Pilot Study

Because formation of rocks is part of a cyclic system, students' representations using the software KnoW should have shown a cyclic sequence of processes. However, such representations were reached by none of the groups when they were supposed to have completed the activity. For example, the map in Figure 4a exemplifies a situation in which students represent processes of the



Comments:

- Note that each rectangle in the map represents a text composed by students in the resources environment.
- "Ha'ela stream", "Palmahim beach" and "Great dune in Ashdod" are locations in the field-trip in which students collected evidence.

Figure 4. (a) Example of a KnoW map before the discussion, representing a noncyclic student perception of the crust system. (b) Example of a KnoW map by the same students, after the discussion, representing a cyclic perception of the crust system.

rock cycle (e.g., transportations, lithification), some earth products (e.g., granite, quartz) and locations in the field trip in which they found evidence for such processes and products (e.g., Ha'ela stream, Palmahim beach). The connections in the map show that they relate some of these ideas to a general notion about "material transformation in nature." However, the arrangement of these ideas lacks a flow that shows how material can transform from one earth product to another by geological processes. Moreover, many students had tremendous difficulties in carrying out the assignment, which caused much frustration. Therefore, additional guided discussions of about an hour with each group were conducted with the authors of this study. Using guiding questions, these discussions were aimed at leading the students toward constructing cyclic sequences of processes. After these discussions, students revised their KnoW projects. The results showed considerable progress in students' representations. For example, Figure 4b shows the revised version of the map presented in Figure 4a. Students made an effort to link processes and products to represent a cyclic view of the system using appropriate connections.

Observations and videotape analysis of students' work indicated that the open nature of the task provided an impediment for many students who would have benefited from a more structured task (Kali, 2000). Audiotapes of the discussions with the groups indicated that with appropriate guiding questions, most students were able to understand the cyclic aspect of the earth's crust system. Questions that seemed to have a positive effect in this context were those which stressed the sequential characteristic of processes and products in the rock cycle: i.e., the fact that each output product of one process can serve as input product for another process, creating sequences with a pattern of process → product → process → product. Specifically, during the discussions many of the students easily answered repeated questions which referred to geological events on a relative time scale (i.e., determining which event must have occurred before or after the other). For example, students usually knew how to answer questions such as, "What will be the product of the process you just mentioned?" and "What process produced the material you just mentioned?" Such questions finally enabled students to understand the dynamics of the system and grasp the idea that chains of processes and products can be cyclical.

Another important outcome, indicated by observations of student groupwork, was that for this specific learning activity, the disadvantages of using the computer exceeded its advantages. The largest disadvantage was that during groupwork only one student at a time could manipulate the software. Consequently many students were not fully involved in the learning process. Impediments in groupwork while using the computer have been described in earlier studies. Burbules and Linn (1991), for example, described situations in which students were excluded from the groupwork and natural leaders gained more experience at the expense of other group members. Linn (1995) dealt with such a difficulty by forming activities with groups of two students. In the current study, additional difficulties such as crowded computer labs, slow and malfunctioning computers, and teacher anxiety were also involved. Such difficulties are commonly reported in the implementation of computer-based curricula, and there are many suggested solutions for dealing with them (e.g., Linn & Hsi, 2000). However, in this study we decided to follow an intuitive design principle that calls for using advanced technology only when it is genuinely required. Therefore, a new concluding knowledge integration activity, which was based on the findings of the pilot study and did not require the use of the computer, was developed for the main study.

Learning Materials and Teaching Methods in the Main Study

Following the above design principle, we examined the use of a device, including a magnetic board (80 × 60 cm), magnetic cards, and erasable board markers. The assignment was similar to that of the KnoW activity (students were required to represent all the processes that produce a certain rock); however, this time the activity was guided by structured worksheets. The worksheets (four pages including examples and illustrations) included questions and instructions similar to those used in the pilot study's group discussions, and guided students through the following steps: (a) Make a list of all the processes mentioned in the field-trip booklet. (b) Complete a ''process card'' for each of the processes in the list. (c) Arrange the cards on the magnetic board in a sequence showing stages in the formation of sandstone and draw arrows between the stages. (d) Complete a ''product card'' for each process. (f) Place your product cards in the appropriate places within the process cards and revise your arrows. (Notice that the final product of one process might be starting material for another). A list of tips was also provided in the worksheets including the following guidelines: ''If your card sequence starts with a process, try to think of a product that serves as its starting material''; ''If your card sequence starts with a product, try to think of its forming process''; ''Does this processes-product chain ever end?''

Research Methods

Sample

The sample in the main research included 40 seventh-grade students from a selective school. The school represents a slightly higher socioeconomic background than the Israeli average population.

Research Tool

A systems thinking test in the context of the rock cycle was developed consisting of four questions that correspond to the definitions of systems thinking by Ossimitz (2000) and O'Connor and McDermott (1997). Each question asks students whether they think there is a sequence of processes between two specific earth products. Positive answers require students to construct the sequence of processes using a word bank. Negative answers require students to explain why they think such a sequence does not exist.

The questions are the following: (a) Is there a sequence of processes that can produce sandstone from exposed granite? (b) Is there a sequence of processes that can produce a volcanic rock (like basalt or rhyolite) from grains in a dune? (c) Is there a sequence of processes that can produce granite from exposed rhyolite? (d) Is there a sequence of processes that can produce sandstone from rhyolite? Note that the quartz crystals in rhyolite are very small, and that the quartz grains in sandstone are large.

The word bank (presented in the test in a scattered format to avoid causing students to refer to the list as a given sequence) includes the following processes: burial, erosion, eruption and rapid crystallization, lithification, melting, metamorphism, sedimentation, slow crystallization, transportation, and uplift and exposure.

Appropriate answers for each of these questions are positive because any earth product could transform to another earth product, given an appropriate sequence of processes. For example, an answer representing systems thinking for the third question might include the following explanation: ''Yes, tectonic processes can *bury* the rhyolite rocks into the depth of the earth's crust. As temperature and pressure rise, the rhyolite would be *metamorphosed*. If the tectonic processes continue to *bury* the metamorphosed rock deeper into areas with higher temperatures and pressures, it can eventually be *melted* into magma. Magma can intrude into shallower areas of the crust which are cooler, and to *crystallize there very slowly* to create a rock with large crystals such as the granite." The sequence of processes in this answer includes: burial → metamorphism → further burial → melting → slow crystallization.

It should be stressed that for each question in the test several appropriate sequences can be constructed. For instance, an alternative sequence of processes that would also be considered as a correct answer to this question would be: burial → melting → slow crystallization.

The first question in the test deals with a sequence of processes that was also dealt with in one of the inquiry activities in the rock cycle program. This question was designed to evaluate knowledge gained by students after their engagement with the program. The answers to the other three questions include sequences of processes which were not specifically dealt with in the rock cycle program (students learned about all the processes but were not engaged with constructing these sequences). These questions were designed to evaluate student ability to use systems thinking to solve problems in a novel context.

Procedure

Implementation of the cards activity lasted 4 hours. It was similar to the implementation of the "know" activity in the following aspects: (a) implementation was carried out in half-size classes, (b) students worked collaboratively in groups of 3 or 4, and (c) similar guidance was given to the teachers with respect to their role as facilitators.

To evaluate the effect of this concluding knowledge integration activity on students' systems thinking, the test was used before the activity (after the students completed the rock cycle) and again a short time after the activity (Figure 2). No additional content knowledge was presented to students (except for the cards activity) between the pretest and the posttest. Students were given 20 minutes to complete the test, after a 5-minute explanation by the teacher.

Data Analysis

Following are criteria developed for analyzing students' explanations to their positive and negative answers.

Positive Answers. Explanations for "yes" answers were classified according to the following categories, representing different degrees of completeness of the sequences of processes:

a. Complete: All geological processes are mentioned in a correct sequence.
b. Extra processes: All processes are mentioned in a correct sequence, but extra, inappropriate processes are added at the beginning and/or the end of the sequence. (An example is the following sequence, given as an answer to Question 1: "Sandstone can be formed from granite through the following processes: Erosion → Transportation → Sedimentation → Lithification → Burial." The last process in this sequence is inadequate.)
c. Incomplete: Some processes in the sequence are missing (up to one third of the required processes). The remaining processes appear in correct order.
d. Replaced: One process in the sequence is replaced with an inappropriate process.
e. Illogical sequences: Sequences do not seem to have a logical meaning according to the scientific knowledge.

Explanations of Type a–d were considered to represent different degrees (in descending order) of high-level systems thinking.

Negative Answers. Each student explanation for a “no” answer was characterized by the type of impediment that prevented the student from viewing the rock cycle as a dynamic system. These characterizations were then sorted into categories which represent alternative incorrect models for viewing the rock cycle. Validity was obtained through expert judgment of three expert earth science educators. They evaluated students’ tests individually using the criteria defined by the authors. The few discrepancies that arose were negotiated until agreement was achieved; if agreement was not reached, the data were dismissed.

Following are the categories that arose from this process which were used to sort students’ negative answers. (Examples of student answers in this section were taken from both pretests and posttests.)

- Product isolation model: Each product of the rock cycle is viewed as a stagnant isolated substance which cannot change or be transformed to any other product of the rock cycle system. The criterion for classifying explanations in this category was based on a description of the differences between the products mentioned in the question. For example, “Granite and sandstone are different rocks with different grains and texture, and there is no chance that one formed the other”; “Grains in a dune are seperated to many particals and rhyolite is a solid rock. It cannot be formed from many grains.”
- Process–product isolation model: The system is viewed as having isolated pairs of product–process pieces of knowledge with no relations between pairs. In this model, each product is produced by a certain process but endless chains of successive processes and products are not represented. The criterion for classifying explanations in this category was based on students’ description of the differences between the processes that created each product. Variations included answers describing only one of the processes which is responsible for one product, but not for the other. For example, “Sand dunes cannot produce volcanic rocks because volcanic rocks are formed from volcanic activity. There is no such activity in dunes”; “Granite is formed in slow crystalization and ryolite is formed in fast crystalization. There can never be a sequence of processes which will create granite from rhyolite.”
- Disconnected internal–external model: The system is viewed as having two disconnected components (internal and external) which have no exchange of material between them. The criterion for classifying explanations in this category was based on using terms of internal and external processes: “Because volcanic rocks are formed inside the earth and the grains of the dune are formed on the surface”; “Granite is formed in the depth of the crust and rhyolite is formed outside of the crust, on top of volcanoes. There is no connection between the two.”
- Model lacking burial and melting processes: The rock cycle is viewed as a dynamic system except for one missing link, which transforms exposed material back to the depth of the earth. The criterion for classifying explanations to this category was based on a specific indication of the missing link: “Because it is a one-way process. The grains on the surface cannot go back inside the earth”; “There is no way for the rhyolite to get back to the magma chamber after it erupted in a volcano.”

Individual Improvement. To assess improvement of individual students, each pair of pre–post answers for each of the questions was coded using the following categories.

Improvement in any of the questions was defined as meeting one of the following conditions:

- A shift from any of the alternative incorrect models to a positive answer with explanations of the Type a, b, c, and d.
- A shift to a higher degree of explanation for a positive answer (according to the classification of explanations for positive answers described above).

- A shift from an illogical sequence, to a positive answer with explanations of Type a, b, c, and d.
- A shift from an illogical sequence to one of the alternative incorrect models.
- A shift to a higher level of alternative incorrect model.

No change in any of the questions was defined as meeting one of the following conditions:

- Both answers belonging to the same classification group.
- Shifts between "I do not know" answers to illogical sequences.

Regression was defined as any of the Improvement conditions, appearing in the reverse order. *Impossible to determine* characterized situations in which pairs of answers included at least one answer without an explanation, or one missing answer.

Improvement at the level of an individual student was defined as having at least one pair of pre–post answers showing improvement, provided the student had more improvements than regressions.

Conceptual Framework for Interpretation

Because methods for analyzing students' degree of systems thinking were not found in the literature, it was necessary to develop a new conceptual framework that would allow us to assess the effect of the concluding knowledge integration activity in terms of systems thinking. Our conceptual framework stems from a synthesis between the dimensions of systems thinking defined by Ossimitz (2000) and the elements of systems thinking defined by O'Connor and McDermott (1997). Using these constructs, we built a continuum representing different degrees of systems thinking. Ossimitz (2000) stressed the dimension of dynamic thinking as a critical aspect of systems thinking. We suggest placing this dimension on a continuum in which one side represents a static view and the opposite represents a highly dynamic view of the system. On top of this continuum we suggest superimposing a dimension of interconnectedness corresponding to the elements of systems thinking defined by O'Connor and McDermott (1997). We claim that in the case of the rock cycle, the more an understanding is based on connections between parts of the system, the more it expresses a higher dynamic view of the system. The degree of connectedness can therefore provide a means for determining the degree of dynamics, and vice versa. This combined continuum served as a basis for constructing a rock cycle systems thinking continuum (Figure 5). At the low end of this continuum are negative answers, with explanations classified under the category of Product Isolation Model. Such explanations express a lack of connectedness between parts of the system, indicate poor dynamic thinking, and represent a completely static view of the rock cycle system. At the opposite end of the continuum are answers that include appropriate sequences of processes for Questions 2–4. Such explanations were interpreted as

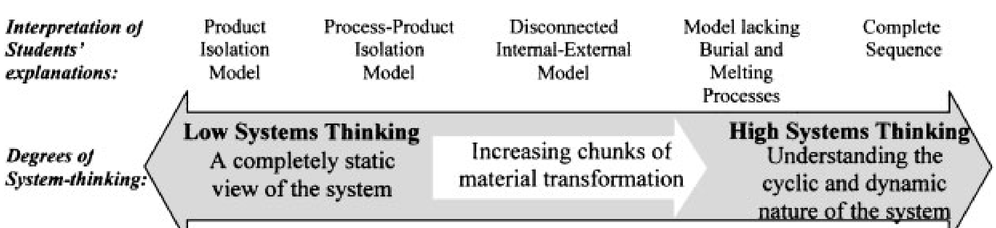


Figure 5. Systems thinking continuum.

representing highly developed dynamic thinking of material transformation within the rock cycle, and a rich understanding of the interconnectedness between parts of the system. With such a view students were able to apply the holistic idea that any material in a system can be a product of any other material, even when they dealt with novel situations. Such understanding was considered to be the highest level of systems thinking in the context of the rock cycle. We suggest that only at this level were students able to meaningfully understand the cyclic nature of the system.

Between these two extremes were explanations indicating different degrees of systems thinking. Explanations classified under the category of Process–Product Isolation Model reflect a view with little dynamics limited to small chunks of material transformation within the rock cycle (between processes and their products). Disconnected Internal–External explanations were placed higher on the continuum because they refer to the rock cycle as consisting of two different subsystems (i.e., the internal and the external system), which allows for larger chunks of material transformation within these subsystems. The most sophisticated alternative incorrect model concerning material transformation within the rock cycle was the Model Lacking Burial and Melting Processes, in which students viewed all the material transformation within the rock cycle, except for one link (burial and melting of rocks). Therefore, they were placed higher than Disconnected Internal–External explanations, just below the highest level of the systems thinking continuum.

Students' alternative incorrect models of the rock cycle described above were not interpreted as misconceptions (e.g., Clement, 1982) or naive theories (e.g., McCloskey, 1983) about the earth's crust. Rather, placing these models on a continuum reflects our view that such models can serve as a basis for developing more sophisticated models, until the highest level of understanding the cyclic nature of the system is reached. The progression within this continuum is considered a result of adding connections between pieces of knowledge, leading to higher levels of integrated knowledge. Such a view supports a perspective described by Smith, diSessa, and Roschelle (1993), who emphasized the continuity between the knowledge of the novice and the knowledge of the expert. They argued that the shift from "single units of knowledge to systems of knowledge with numerous elements and complex substructure" is a result of a "gradual change, in bits and pieces" (p. 148).

Interpretive Results

In this section we present the results of the study, together with our interpretation of their meaning, based on the conceptual framework of the systems thinking continuum described above. We commence by presenting frequency distributions of students' answers and explanations, followed by a comment about how we interpret the aspect of answering positively or negatively. We continue with an analysis of students' systems thinking at different stages of the study, and an interpretation of the effect of the knowledge integration activity on this type of thinking. A discussion about the relationship between students' systems thinking and their general awareness of holistic aspects of the system follows. Finally, we present an analysis of the curriculum materials, which retrospectively explores curricular elements in the rock cycle program and in the knowledge integration activity. This analysis seeks to understand better the potential effect of the design of these curricular elements on students' systems thinking.

Frequency Distribution

The above categorization of students' positive and negative answers and explanations, before and after the concluding knowledge integration activity, yielded the frequency distribution summarized in Table 1.

Table 1
Summary of results

Answers	Question 1 (Familiar Context)		Average of Questions 2–4 (Novel Context)	
	Pre (%)	Post (%)	Pre (%)	Post (%)
Yes				
High-level systems thinking (Explanations a–d)	60	66	7	29
No explanation	5	5	5	4
Illogical explanation	13	5	7	4
Total of "yes" answers	78	76	19	37
No				
Model lacking burial and melting processes	0	4	13	6
Disconnected internal–external model	0	0	10	4
Process–product isolation model	0	2	10	12
Product isolation model	0	3	20	7
No explanation	8	2	7	6
Total of "no" answers	8	11	60	35
Miscellaneous				
"I don't know"	11	8	16	13
Answers showing misunderstanding of question	0	0	1	5
Students who did not answer question	3	5	4	10
Total miscellaneous answers	14	13	21	28

Students' decision to answer positively or negatively was considered as reflecting their general awareness of material transformation dynamics in the rock cycle. It was postulated that students who answered "yes," regardless of their explanation, had such awareness and that students who answered "no" lacked it. Such awareness could have resulted from different levels of understanding. The lowest level could have been based on declarative knowledge. If students knew that the system is cyclic, they could have applied this knowledge to the conclusion that any material can be a product of any other material, and therefore answer positively. On the other hand, the highest level of such awareness could have been based on procedural knowledge. If students understood all the geological processes and the relations between processes and products, they could have used this knowledge to construct relatively long sequences of material transformation in the rock cycle. With such an understanding, they could have provided appropriate sequences of processes to their positive answers, indicating high levels of systems thinking. To minimize errors of interpretation, we decided to refer to all "yes" answers as indicating a general awareness of the dynamic and cyclic nature of the rock cycle, and to base further interpretation about students' systems thinking on their explanations.

Students' Systems Thinking after the Rock Cycle Program

Table 1 reveals that most students (60%) were able to reconstruct the relatively large sequence of processes required to answer the first question appropriately. Because this question deals with a sequence familiar to students from the inquiry activities and field trip, we refer to this outcome as an indication to a reasonable gain of knowledge after the rock cycle program. However, a different picture is revealed in an analysis of students' answers to Questions 2–4, which required students to construct rock cycle sequences in novel contexts. The results indicate that before the knowledge integration activity, students' general awareness of the dynamic nature of the rock cycle was low. That only 19% of the answers were positive, whereas 60% were negative, indicates a lack of such awareness. Despite all the activities within the program that dealt with material transformation, many students did not internalize the idea of the dynamic and cyclic nature the system at this stage. Moreover, students' explanations for their answers to Questions 2–4 indicate that before the knowledge integration activity, most students who gave comprehensible explanations were on the lower side of the systems thinking continuum, representing a completely static view of the system. This is evidenced by the percentage of answers at the extreme ends of the continuum: only 7% at the high extreme and 20% at the low extreme (Product–Isolation model explanations).

Effect of Concluding Knowledge Integration Activity

A comparison of students' answers and explanations in the pretest and the posttest indicates that after the knowledge integration activity with the magnetic cards, students' views of the rock cycle meaningfully improved. That the percentage of negative answers for Questions 2–4 decreased from 60 to 35, and the percentage of positive answers increased from 19 to 37 (Table 1), indicates that students became more aware of the dynamic and cyclic nature of the rock cycle. Furthermore, students' ability to construct sequences of processes representing material transformation in relatively large chunks significantly improved. This is indicated by a sharp increase in the percentage of answers at the high extreme of the systems thinking continuum, from 7 to 29, as well as a sharp decrease in the percentage of answers at the low extreme, from 20 to 7 (Table 1).

To obtain further insight about the concluding knowledge integration activity's effect, we conducted an analysis of individual student performance. On the basis of the definition described above for improvement, we found that 76% of students improved their systems thinking of the rock cycle. An analysis of types of individual improvement indicated that 74% of these improvements represented a shift from alternative incorrect explanations to high-level systems thinking.

Relation between Systems Awareness and Systems Thinking

Our analysis of students' understanding of the rock cycle included two aspects: (a) general awareness of the dynamics in the rock cycle, depicted by their choice of positive or negative answers; and (b) their systems thinking, depicted by the placement of students' explanations on the systems thinking continuum. To examine the relations between these aspects, we compared their relative proportion in this study with such proportion in the pilot study. Figures 6a and 6b summarize these comparisons. The comparison indicates that different types of knowledge were obtained in these studies. The higher percentages of "yes" answers among students who participated in the pilot study reflect a higher awareness of the dynamic nature of the rock cycle compared with students who participated in the main study (Figure 6a). However, the higher percentages of appropriate explanations (the highest level in the systems thinking continuum) among students in the main study reflect their higher degree of systems thinking (Figure 6b).

Several potential factors might have affected the character of students' knowledge in the two samples (e.g., teaching, school atmosphere, the higher socioeconomic background of students in the main study). Therefore, it is impossible to ascribe the differences between the types of knowledge to the interventions involved in these studies. However, that students with higher awareness achieved lower systems thinking (pilot study) and students with lower awareness achieved higher systems thinking (main study) is somewhat surprising. One would expect that if students have reasonable knowledge of geological processes and their products (which was the case in these two samples, as described above), the awareness of the dynamic and cyclic nature of the system should facilitate gaining systems thinking. In other words, the general notion about

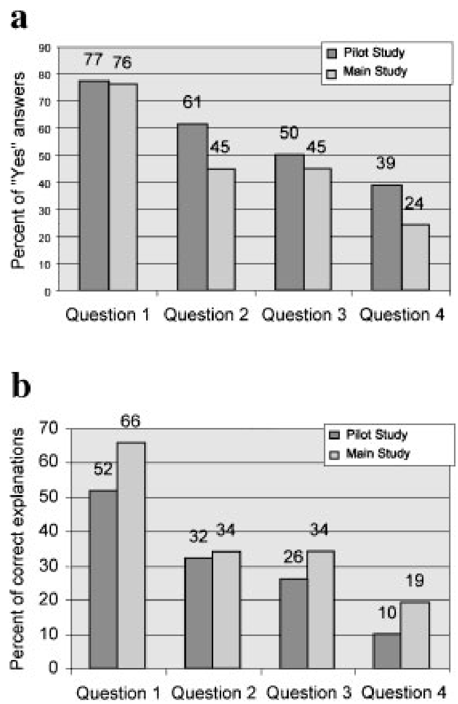


Figure 6. (a) Frequency distribution of "yes" answers in the two studies. (b) Frequency distribution of correct explanations (appropriate sequences) for "yes" answers in the two studies.

material transformation through processes in the rock cycle should have assisted students who were familiar with these processes in constructing the required sequences. However, the comparison between types of knowledge gained in the two studies implies that this is not the case. Students' higher awareness in the pilot study did not lead to improved systems thinking. Rather, higher systems thinking was achieved by students in the main study who had lower awareness of the dynamic nature of the system. The implication of this finding is discussed below.

Retrospective Analysis of Curriculum Materials

The above analysis raises the following question: What in this 4-hour knowledge integration activity with magnetic cards enabled students to improve their systems thinking of the rock cycle? To answer this question, let us first consider the opposite question: What was missing in the rock cycle program which prevented students from understanding the dynamic and cyclic nature of this system?

The latter question can be answered by analysis of the three types of activities incorporated within the rock cycle program (i.e., inquiry of geological processes, construction of the rock cycle activity, and the field trip) using the systems thinking continuum suggested earlier. During the inquiry activities, students dealt with chunks of material transformation that included an input product, a process, and an output product. Such relatively small chunks of material transformation were named Input → Process → Output chunks (IPO chunks). For example, the IPO of volcanic processes consisted of the magma as input, volcanism as the process, and volcanic rocks as the output.

After an inquiry activity of each geological process, students conducted the second type of activity, the construction of the rock cycle, in which they were engaged with integration of the newly studied IPO with IPOs studied in former lessons. The different IPO chunks connected to each other in students' diagrams represented dynamic transformation of material through long sequences of processes. For example, after learning about volcanic processes, students should have drawn an arrow representing volcanic processes, starting from the magma (input) toward exposed volcanic rocks (output). Such a sequence represents a short IPO chunk. However, after learning the next type of processes, i.e., weathering, students should have added another arrow to their diagram, starting from exposed rocks (input) toward weathering products such as rounded pebbles (output). The exposed rocks, which included exposed volcanic rocks, were the output of the first IPO and the input of the second IPO. In this manner students' diagrams should have represented longer sequences of material transformation, which for this example included the following processes and products: magma → volcanism → exposed rocks (including volcanic rocks) → weathering → rounded pebbles. However, our results indicate that at this stage most students were unaware of the meaning of their representations, i.e., the dynamic nature of the system.

This lack of awareness may have resulted from the following: (a) While engaged in this activity, students perceived IPOs as independent chunks of material transformation without fully considering their components (each of the processes and products). This could have prevented them from viewing material transformation dynamics in larger chunks. (b) Because the activity required students to integrate newly learned IPOs with IPOs studied in former lessons, the activity might have caused them constantly to assimilate new knowledge without having an opportunity to accommodate it to their cognitive knowledge structures. Lewis (1991) described a situation in which students combine new information at the level of local knowledge but do not integrate the pieces of that knowledge to build a more robust and cohesive view. She indicated that such knowledge was gained by a specific type of student, namely "progressing" students, who tended to accept ideas that did not mesh with their prior knowledge. The current analysis refers to this knowledge as a product of the activities in which students were engaged with at a specific stage of learning (i.e., before the concluding knowledge integration activity).

A comparable analysis using the same terms (i.e., size of material transformation chunks, accommodation, assimilation) can be performed for the magnetic cards concluding knowledge integration activity. The analysis indicates that this activity served as a continuation of students' learning processes and used the foundations acquired through the rock cycle program to upgrade students' systems thinking. According to this analysis, the reasons for the success of this activity in promoting systems thinking among students are the following: (a) Instead of integrating IPO chunks, as in the construction of the rock cycle activity, students were encouraged to differentiate such chunks. Only after representing all the smallest parts of the system on separate magnetic cards were students able to integrate them meaningfully in a cyclic and dynamic system. We suggest that this differentiation was a key issue in the success of the knowledge integration activity. Linn and Eylon (1996) also described the significance of differentiation as a step toward knowledge integration. In a longitudinal case study, they showed that naturally occurring differentiation and integration processes served as basic elements in the conceptual change of a specific student. In the current study, though, such processes were implicitly required from students through the knowledge integration activity. The current study supports the notion of this dual process and broadens it to include an effect on students' systems thinking as well. (b) When the knowledge integration activity was conducted, all knowledge about geological processes and their products had already been studied and further emphasized in the concrete context of the field trip [for the effect of the field trip on learning, see Orion and Hofstein (1994)]. The cards activity might have provided students with an opportunity to accommodate elements of knowledge which were not in equilibrium with existing knowledge structures.

Conclusions and Implications

The current study shows that getting meaningful understanding of the rock cycle requires high levels of systems thinking. Despite activities meant to promote systems thinking in the rock cycle, few students reached such levels at the end of the program. Our analysis of the curriculum materials indicates, however, that these activities did provide students with useful cognitive frameworks, which were subsequently used by students for developing higher levels of systems thinking during the concluding knowledge integration activity. By engaging students in a dual process of (a) differentiating their existing knowledge into the smallest components of a system, and (b) reintegrating in a systems context, this 4-hour activity succeeded in meaningfully leveraging students' understanding of the dynamic and cyclic aspects of the rock cycle. Another example of a short-term knowledge integration intervention which followed a knowledge acquisition stage and also caused considerable improvement in students' understanding is described in Bagno and Eylon (1997). An additional finding of this study, which has important implications for science education and can inform curriculum design, is the finding that general awareness of the holistic aspect of a system does not necessarily foster systems thinking. Many curricula start by stating general rules of a system, and subsequently deal with each of system's components, taking for granted students' understanding of the systems aspect (Kali, 2000). The current findings contradict this view. Rather, we suggest that systems-based curricula design should include two stages: (a) a gradual knowledge building stage in which each of the system's components is studied in an inquiry process and gradually integrated into a holistic depiction of the system, and (b) a differentiation and reintegration concluding stage, which includes the dual process discussed above.

The finding of the current study, which shows that with appropriate teaching students were able to acquire systems thinking in the context of the rock cycle, is encouraging. It provides a positive answer to the question raised by Gudovich (1997) as to whether such thinking can be learned. Moreover, students' systems thinking in this context provides a first step in their holistic understanding of the dynamic and cyclic aspects of larger earth systems. Such understanding is a main component for informed decision making required in many environmental issues with which our society is increasingly confronted. This stage of informed activity within the earth systems, which corresponds to Ossimitz's (2000) "steering systems" dimension, must be deeply rooted in meaningful understanding of the earth as a system.

Further study with larger samples is needed to explore the relation between knowledge integration and systems thinking. In addition, the effect of learners' awareness of holistic aspect of a system on their ability to understand it in a systems manner, which was questioned in this study, requires deeper examination. Finally, a methodologic contribution of this study to the learning sciences is the development of the systems thinking continuum. This development can provide powerful means for further study of systems thinking in other scientific domains. Continuums such as the one suggested in the current study can be constructed in any systems-based context. The levels of systems thinking along such continuums can be determined by learners' ability to construct long causal relationship sequences and networks, which allow for dynamic thinking in various systems. Low systems thinking would include indications that a learner's knowledge of a system is based on understanding components of the system, without an understanding of the causal relations between them, and therefore indicate a static view. Higher degrees of systems thinking would include indications of learners' understanding of larger and larger chunks of dynamics in the system. Building such continuums and comparing their constructs across various scientific subject matters might lead to deeper insight of this unique type of thinking. Such insight could provide further suggestions for designing curriculum materials that deal with the cognitive challenges involved in systems thinking.

References

Ault, C.R. (1998). Criteria of excellence for geological inquiry: The necessity of ambiguity. Journal of Research in Science Teaching, 35, 189–212.

Bagno, E. & Eylon, B. (1997). From problem-solving to a knowledge structure: An example from the domain of electromagnetism. American Journal of Physics, 65, 726–736.

Bloom, B.S. (Ed.). (1984). Taxonomy of educational objectives. 1: Cognitive domain. White Plains, NY: Longman.

Burbules, N.C. & Linn M.C. (1991). Science education and the philosophy of science: Congruence or contradiction? International Journal of Science Education, 13, 227–241.

Clement, J. (1982). Algebra word problem solutions: Thought processes underlying a common misconception. Journal for Research in Mathematics Education, 13, 16–30.

Dror, Y. (1984, October). A system approach towards the integration of curriculum elements. Paper presented at the international seminar on School Based Curriculum Development, Tel Aviv University.

Emery, R.E. (1992). Parenting in context: Systemic thinking about parental conflict and its influence on children. Journal of Consulting and Clinical Psychology, 60, 909–912.

Faughnan, J.G. & Elson, R. (1998). Information technology and the clinical curriculum: Some predictions and their implications for the class of 2003. Academic Medicine, 73, 766–769.

Fordyce, D. (1988). The development of systems thinking in engineering education: An interdisciplinary model. European Journal of Engineering Education, 13, 283–292.

Fortner, R.W. & Mayer, V.J. (1998, July). Learning about the earth as a system. Proceeding of the Second International Conference on Geoscience Education, Hilo, HI.

Frank, M. (1999). Engineering systems view: Characteristics and learning processes. Unpublished dissertation, Technion Israeli Institute of Technology, Haifa, Israel.

Graczyk, S.L. (1993). Get with the system: General systems theory for business officials. School Business Affairs. 59, 16–20.

Gudovich, Y. (1997). The global carbon cycle as a model for teaching ‘‘earth systems’’ in high school: Development, implementation, and evaluation. Unpublished master’s thesis, Weizmann Institute of Science, Rehovot, Israel (in Hebrew).

Kali, Y. (2000). Learning processes in knowledge integration: A new learning program in earth sciences for junior high school students. Unpublished doctoral dissertation, Weizmann Institute of Science, Rehovot, Israel.

Lewis, E.L. (1991, April). The development of understanding in elementary thermodynamics. Paper presented at the annual meeting of the American Educational Research Association, Chicago, IL.

Lewis, J.P. (1998). Mastering project management: Applying advanced concepts of systems thinking, control and evaluation, resource allocation. New York: McGraw-Hill.

Linn, M.C. (1995). Designing computer learning environments for engineering and computer science: The scaffolded knowledge integration framework. Journal of Science Education and Technology, 4, 103–126.

Linn, M.C. & Hsi, S. (2000). Computers, teachers, peers: Science learning partners. Hillsdale, NJ: Erlbaum.

Linn, M.C. & Eylon, B. (1996). Lifelong science learning: A longitudinal case study. In G. Cottrell, Proceedings of CogSci96, pp. 597–600. Mahwah, NJ: Erlbaum.

Linn, M.C., Songer, N.B., & Eylon, B. (1996). Shifts and convergences in science learning and instruction. In R. Calfee & D. Berliner (Eds.), Handbook of educational psychology. Riverside, NJ: Macmillan.

Mayer, V.J. (Ed.). (2002). Global science literacy. Dordrecht: Kluwer Academic.

McCloskey, M. (1983). Naive theories of motion. In D. Gentner & A. Stevens (Eds.), Mental models (pp. 299–323). Hillsdale, NJ: Erlbaum,.

O'Connor, J. & McDermott, I. (1997). The art of systems thinking. San Francisco: Thorsons.

Ossimitz, G. (2000, August). Teaching system dynamics and systems thinking in Austria and Germany. Proceedings of the 18th International Conference of the System Dynamics Society, Bergen, Norway.

Orion, N. (1993). A model for the development and implementation of field trips as an integral part of the science curriculum. School Science and Mathematics, 93(6), 325–331.

Orion, N. (1998). Implementation of new teaching strategies in different learning environments within the science education. In Proceedings of the International Conference of Secondary Education in Portugal: Shaping The Future: Politics Curricula Practices, pp. 125–139. Evora, Portugal: Ministry of Education.

Orion, N. & Hofstein, A. (1994). Factors that influence learning during a scientific field trip in a natural environment. Journal of Research in Science Teaching, 31, 1097–1119.

Senge, P.M. (1998). "Fifth discipline": Review and discussion. Systemic Practice and Action Research, 11, 259–273.

Shear, L. (1998, April). Debating life on Mars: The knowledge integration environment (KIE) in varied school settings. Paper presented at the annual meeting of the American Educational Research Association, San Diego, CA.

Smith, J. P., diSessa, A., & Roschelle, J. (1993). Misconception reconceived: A constructivist analysis of knowledge in transition. Journal of the Learning Sciences, 3, 17–32.

Songer, N.B. & Linn, M.C. (1991). How do students' views of science influence knowledge integration? Journal of Research in Science Teaching, 28, 761–784.