Developing Explanations and Developing Understanding:

Students Explain the Phases of the Moon Using Visual Representations

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Abstract

This paper presents a theoretical model of the process by which students construct and elaborate explanations of a scientific phenomenon using visual representations. The model describes progress in the underlying conceptual processes evident in the students' explanations as a reorganization of fine-grained knowledge elements based on the Knowledge in Pieces perspective (diSessa, 1993). Pairs of students, aged 10-14 years, engaged in activities that required them to generate and elaborate visual representations to explain scientific phenomena. The core case study involved a pair of 11-year-olds (fifth graders) who generated visual representations to explain the phases of the moon and collaboratively elaborated and improved their representations and explanations. The model describes the process of developing explanations as consisting of iterations of temporarily stable stages, interpreted as temporary plateaus of coherence. The progression from one temporary coherent structure to the next is described as the increase of *Resolution* and/or the increase of *Range* of coherence underlying the explanation. Resolution and Range are two newly defined theoretical constructs of the model. The model accounts for the continuity in the students' developing understanding from a rough intuitive to a more advanced understanding and highlights the productive nature of their intuitive knowledge resources.

This paper proposes a theoretical model of the process by which students construct and elaborate explanations of a scientific phenomenon by generating visual representations and reasoning with them. The working assumption is that explanations are external manifestations of the current state of understanding, and, therefore, changes in explanation provide cogent data on changes in underlying conceptualization. The theoretical model intends to account for the real-time generation of explanations and their progression from primitive to advanced, and to describe the conceptual dynamics underlying this process.

To introduce the main issues set out in this paper, I begin by illustrating briefly the conceptual phenomena accounted for by this model and highlighting two focal questions relevant to this investigation.

During the research sessions students were asked to draw visual representations (a diagram, detailed drawing, sketch) explaining the phases of the moon. The students produce drawings and then use them to explain the phenomenon to others, and in so doing, they rely on their knowledge resources. It may be assumed that the students had knowledge resources from a variety of sources. For example, they knew something about the moon's appearance at night and during the daytime based on direct personal observations. Because basic science is part of the Israeli curriculum, they probably also acquired some factual knowledge about the moon's revolution around the Earth and the Earth's rotation on its axis. They might also have incidental knowledge, such as the memory of a picture in a science book they enjoyed. However, when asked to explain the phases of the moon, not *all* the students' relevant knowledge resources are activated. Some are ignored or simply not elicited even though there may be evidence, from other contexts, that these knowledge resources exist. Some knowledge resources may be more important to the student than others. In any case, the students draw on available knowledge resources to produce explanations that, perhaps for the moment, feel satisfying to them. The first focal question is therefore: *How do we capture, in a realistically complex form, the conceptual structure behind students' explanations?*

The students in my research sessions worked in pairs. Initially, they worked alone on generating a personal explanation and drawing. Later, I asked them to discuss their drawings and explanations together and then develop shared representations and explanations. I, as the researcher and the session instructor, occasionally stepped in to challenge the students' explanations, to ask questions, and to initiate discussions on various points. This process involved students in providing a series of explanations in which they changed and refined their reasoning. Observing students during this process, the general impression was that each explanation felt satisfactory at the time and better than previous ones. The second focal question therefore is: *How do we describe the conceptual dynamic behind the progression of explanations?*

The model developed here seeks to provide helpful, if necessarily incomplete, responses to the two focal questions outlined above. In the next section, I use the two focal questions to help highlight and position the research in science and mathematics education relevant to the current investigation.

BACKGROUND

1. How Do We Capture, in a Realistic Complex Form, the Conceptual Structure Behind Students' Explanations?

The first question concerns the conceptual structure underlying students' intuitive explanations and the way conceptual resources get cued and used in these explanations. The fundamental constituents and attributes of students' intuitive knowledge are central issues in conceptual change research (e.g., Carey, 1988; 1999; Nersessian, 1989; Strike & Posner, 1990; Vosniadou & Brewer, 1992; Wiser, 1988; and diSessa, 1993). Conceptual change research is commonly divided into two theoretical perspectives: “knowledge-as-theory” and “knowledge-as-elements” (Ozdemir & Clark, 2007). “Knowledge-as-theory” generally describes intuitive knowledge as coherent, systematic, and even theory-like; the “knowledge-as-elements” perspective sees intuitive knowledge as diverse, fragmented, and of limited coherence.

In general, “knowledge-as-theory” perspectives argue that learners have well developed coherent structures grounded in persistent ontological and epistemological commitments (Posner, Strike, Hewson & Gertzog, 1982; Strike & Posner, 1990; Carey, 1985; Vosniadou & Brewer, 1992; Vosniadou, Vamvakoussi, & Skopeliti, 2008). These structures are unconsciously developed as a result of daily experiences and have the explanatory power to make consistent predictions and explanations across different domains.

According to the “knowledge-as-elements” perspective, students’ understanding consists of collections of multiple quasi-independent elements. DiSessa’s “knowledge in pieces” (KiP) theory (diSessa, 1993) is the leading “knowledge-as-elements” account and has been extended by other researchers (e.g., Sherin, Krakowski, & Lee, 2012; Hammer, Elby, Scherr, & Redish, 2005; Parnafes, 2007; Wagner, 2006). A key commitment of KiP’s epistemological view is the claim that the intuitive conceptual structure of the student is a complex system. Different KiP theories describe complex conceptual ecologies (diSessa, 2002) with a wide diversity of fine-grain “pieces.” These intuitive knowledge pieces are context sensitive so that focusing attention on different aspects, questions, and settings of a given scientific phenomenon can cue different pieces of knowledge and hence different explanations.

The present research seeks to contribute to the conceptual change literature and in particular to extend the knowledge-as-elements (KiP) perspective. It examines the progression of students' explanations in a way that captures the complexity and diversity of the knowledge resources on which the students drew and provides a detailed description of the changes in knowledge resources populating the construction of an explanation.

2. How do we Describe the Conceptual Dynamic Underlying the Progression of Explanations?

This question concerns the dynamics and changes in the conceptual system that lead to shifts and progress in explanations, from a previous satisfying explanation, to another, even better explanation. In addition to the question of the nature of intuitive knowledge discussed previously, conceptual change research also examines the process of development from a naïve understanding to a more advanced scientific understanding (recent perspectives are presented in the *International Handbook of Research on Conceptual Change,* Vosniadou, 2008). How does intuitive knowledge change and develop into normative knowledge? How does an advanced explanation develop from a less advanced or primitive explanation?

Generally speaking, proponents of the "knowledge-as-theory" perspective argue that students' relatively coherent knowledge structures may be subject to radical change through various mechanisms, some of which require the replacement of prior conceptions. For example, corresponding to Kuhn's (1962) notion of paradigms shifts, Posner, Strike, Hewson and Gertzog (1982) and later Strike and Posner (1990) suggest that a new conception can replace an existing one if the new one is intelligible, plausible, and fruitful. Carey's (1985) concept of radical restructuring, defined as a process of abandoning an old conception and replacing it with a new one, aligns with this view.

Consistent with the "knowledge-as-theory" perspective is the view that students' knowledge consists of conceptions, some of which are wrong. Pfundt and Duit (2009) reviewed over 8000 studies, most of which characterized students' knowledge as involving incorrect conceptions of mathematical and scientific principles. Conceptions (and misconceptions or intuitive conceptions) are thought of as robust, intact elements of cognition that demonstrate resistance to instruction and through the process of conceptual change often become replaced by more normative conceptions.

The “knowledge-in-pieces” perspective views conceptual development differently. Learning is conceived as the reorganization and re-contextualization of the pieces of a student’s conceptual repertoire. The pieces themselves are potentially productive building blocks out of which new knowledge can be constructed (Smith, diSessa & Roschelle, 1993), and thus in general, are not replaced.

KiP researchers often investigate learning and mechanisms of learning with reference to small time-scales and multiple stages (e.g. Parnafes, 2007; Izsák, 2005; Wagner, 2006). Hammer, Elby, Scherr and Redish (2005), for example, distinguish a manifold ontology from a unitary ontology. A unitary ontology takes an intuitive conception or misconception as a cognitive unit and investigates what happens to it (changed, replaced, etc.) A manifold ontology, on the other hand, might accept some “conception-level” description of knowledge, but might also decompose a conception and analyze the organization of its fine-grained components and how they are reassembled as a more advanced understanding.

The model presented here seeks to describe the conceptual dynamic underlying the progression from less to more complex explanations, from naive to more normative understandings. It was developed in dialogue with the KiP general framework and, again, seeks to extend that framework by developing a more detailed schematization of the generation and elaboration of explanations, especially those using visual representations.

The two focal questions that frame this inquiry will continue to serve as the backdrop for this investigation and I return to them throughout the study.

DEVELOPING EXPLANATIONS, DEVELOPING UNDERSTANDING – A THEORETICAL MODEL

Overview

The theoretical model described in the paper is the product of fine tuning multiple iterations of development and application of new theoretical constructs to the data corpus. The model describes the underlying conceptual dynamic of the development of explanations as a progression of temporary coherent structures of activated knowledge elements. A student trying to understand a phenomenon goes through iterations of explanations, with temporarily stable stages of comfort and satisfaction in between. This comfort is interpreted, within the model, as a temporary plateau of coherence. The progression from one temporary plateau of coherence to the next (judged-to-be-better) is characterized by an increase in the *Resolution* and in the *Range* of coherence underlying the explanations. Following is a detailed description of the main features of this model: local or temporary coherence, the epistemological status of knowledge pieces, types of knowledge pieces, and the *Resolution* and *Range* of coherence.

An Explanation as Local Coherence

A student's (temporary) explanation is viewed in this model as a collection of activated knowledge pieces that the student feels fit together, and hence the explanation feels sensible and satisfying. Versions of this view are supported by other theorists. The Node/Mode framework (Sherin, Krakowski, & Lee, 2012) was developed to study a very similar phenomenology to the current study, namely the construction of scientific explanations by students during clinical interviews. Among other matters, this framework examines the question of student convergence on specific explanations. The framework conceptualizes student reasoning as drawing on sets of knowledge pieces called Nodes. These nodes produce temporary explanatory structures termed Dynamic Mental Constructs

(DMCs), which represent the underlying conceptual structures of a student’s explanation. Their analysis showed that when explaining the seasons and climate, students assembled different DMCs into different explanations, shifting between explanations from one moment to the next. One of the principles related to the question of “convergence,” namely why students’ explanations consolidate around a specific DMC, is that students feel the explanation should be consistent with all the known facts.

Thagard (2007) elaborated the idea of consistency or coherence and modeled a way to weigh and judge the quality of scientific explanations. He defined coherence as “a relation among mental representations, including sentence-like propositions and also word-like concepts and picture-like images. Coherence is a global relation among a whole set of representations, but arises from relations of coherence and incoherence between pairs of representations” (p. 29). Thagard (2000, 2007) proposes a computational and naturalistic account of coherence. He maintains that mental elements can cohere (fit together) or incohere (resist fitting together), and that the problem of coherence consists of dividing a set of elements into accepted and rejected sets in a way that maximally satisfies multiple constraints.

Thagard is mainly concerned with scientific knowledge and not with students’ explanatory resources, which is the particular focus of the present model. Focusing on scientific knowledge rather than on individual’s knowledge entails an important difference between Thagard’s perspective and the current model with regard to the activation of knowledge and its availability. Thagard’s computational model suggests looking for an optimal set of cohering elements from among the relevant knowledge elements, claiming that maximizing coherence is a matter of “maximizing satisfaction of a set of positive and negative constraints” (Thagard, 2000, p.15). The current model, as well as that of Sherin et al. 2012), suggests that knowledge pieces are cued by context and are not “available” at all times. Hence, some knowledge pieces are cued by a specific context and setting and form a temporary coherence, while other, different knowledge pieces, are cued as the activity unfolds, because of different contextual cues and form a different temporary coherence.

Despite the differences, Sherin et al. (2012) suggest that the idea of coherence as an underlying relation against which explanations can be judged may be relevant to students' developing explanations.

The terms “coherence” and “consistency” are also core concepts of the “knowledge-as-theory” view where knowledge structures are considered stable across various contexts and situations. In contrast, the consistency and coherence of knowledge pieces in the present model resembles what Hammer et al. (2005) termed "local coherence." Local coherence means that the activation of knowledge pieces and formation of specific coherences are context sensitive. In one particular situation certain knowledge pieces may be cued and activated and a specific local coherence formed; a few moments later, triggered by a different context (e.g., a different question, a drawing showing a different representation), another explanation may be constructed based on a different local coherence. Sherin et al. (2012) developed a similar notion within an interview context: A DMC is a temporary conceptual structure underlying an explanation that may exhibit consistency within its nodes but which may shift to a different DMC as the interview unfolds.

Epistemological Status of Knowledge Pieces

Susan Haack (1993) argues that not all knowledge elements make an equal contribution to the justification of beliefs and that sense experiences deserve a special, if not completely privileged, role. Personal experiences, for example, are often taken to be irrefutable.

More generally, Sherin et al. (2012) note that students may rely on certain explanations if they attach a high degree of importance and reliability to particular, even idiosyncratic, knowledge pieces, and may make finding an explanation that incorporates or is consistent with that knowledge piece a priority.

Kapon and diSessa (in revision), studying students' reasoning induced by instructional analogical sequences, follow on the notion of priority in the knowledge-in-pieces model (diSessa, 1993). They claim that explanations are accepted or rejected on the basis of an individual's prioritized conviction concerning the knowledge pieces that are invoked. Thus, knowledge pieces that are felt to be certain are said to have high priority, and those that are plausible but not indubitable are described as having low priority. They distinguish between intrinsic priority and contextual priority. The former is the degree of inherent confidence in a certain knowledge piece, and the latter is the degree of confidence in the applicability of the knowledge piece in the relevant context.

In line with these arguments, the current model views the stability and persistence of an explanation as determined to a great extent by the epistemological status that the student implicitly attaches to some of its components. This variance in epistemological status implies that when constructing explanations students may perceive higher-status knowledge pieces as incontrovertible, and make other pieces fit in with them—or if this cannot be done, exclude them.

Knowledge Pieces Underlying the Explanations

In order to track the organization and reorganization of a student's explanations, the explanations need to be decomposed into fine-grained elements—pieces of knowledge. Knowledge pieces may be classified into different categories to capture their different properties within the dynamic interaction. Drawing from the larger literature on cognitive structures, the categories of knowledge pieces used for the model I develop here are: propositions, general schema, mental models, and mental images (see the Appendix).[i] The list is not meant to be exhaustive or exclusive but functional: These are the categories of knowledge pieces that capture much of the conceptual dynamics involved in the case study in question of students' reasoning about the phases of the moon.

Propositions. Propositions are knowledge elements in the form of declarative sentences, which claim that a given state of affairs is true. The content of propositional knowledge can be acquired in several ways:

- Learned facts – Facts can be learned at school, from books, through interactions with adults, siblings, or friends, and from any other resource that the learner considers reliable. For example: "The moon orbits the Earth in 30 days," "Light travels in straight lines."
- Incidental personal knowledge – Some propositions are based on personal incidents. For example, a student who used to phone her grandmother in America knew that "When it is day in Israel, it is night in the U.S."
- Direct personal experience – These are propositions based on direct sensory experiences involving aspects of the phenomenon. For example, students provided statements based on their own direct experiences: "There are days when the moon can also be seen during the day," "The shape of the moon changes gradually."

General schemas. Commonsense knowledge is usually construed as based on general schemas—general abstractions that provide a sense of how things in the world work. One subset of the general schemas identified and elaborated in the present study is diSessa's phenomenological primitives or p-prims (1993). P-prims are taken to be simple generalized abstractions generated from students' experience and applied to a wide *Range* of phenomena. A prototypical example is the "Ohm's p-prim," which states that more effort begets more results and that resistance to effort begets less results. The Ohm's p-prim applies to many different circumstances, including moving objects (pushing harder causes greater speed) and personal psychology (if you make efforts in your studies you will gain higher grades).

Some of the general schemas identified in the data are or may well be p-prims, but some of them are not. For example, when a student infers that the moon is illuminated in a specific way because the sun shines on the moon and lights its surface, I would suggest he is relying on a general schema of *Illuminating* (how a source of light illuminates the surface of an object). *Illuminating* does not have critical characteristics of a p-prim. In particular, p-prims are non-propositional and self-explanatory: Something happens because "that's the way things are.". *Illuminating* on the other hand refers to a spectrum of general knowledge claims students make about light—they make gestures to show how the light travels and illuminates an object, they explain that light travels in straight lines, and that it can reach only some parts of an object and not others. In any case, characterizing general schemas as p-prims or non p-prims is not an objective of this study, and it is not necessary for utilizing the model to trace the evolution of explanations. What is important is to identify that a knowledge piece of a distinct and recurrent general structural form is invoked at a particular moment and shapes students' thinking. Therefore, I choose to use the less specific category—general schema—that includes p-prims as well as other general abstractions, which capture the salient aspects of the relevant patterns of thought.

Mental models. In cognitive science much has been written about mental models (e.g., Gentner & Stevens, 1983; Johnson-Laird, 1983). In the current theoretical model, a mental model has a specific, limited meaning. Mental models are mental representations of real or imaginary situations that show analog properties (e.g., properties of a visual presentation) and also are "runnable," that is, they can be the basis of an internal simulation that predicts future states. Mental models can be constructed from perceptions, the imagination, or understanding a discourse (Craik, 1943). Figure 1 represents simple visual representations generated by students that function as mental models. Although the illustrations are static, they typically refer to dynamic systems capable of assuming different states and arrangements. In the current theoretical model, general schemas are usually applied together with mental models to produce inferences. For example, the general schema of *Illuminating* can be applied to the mental model of the moon's orbit around the Earth to infer how the sun illuminates the moon at different points in the moon's orbit.

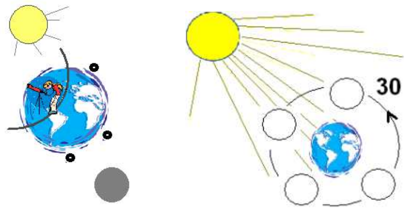


Figure 1 - Examples of visual representations showing some of the mental models used in the analysis. On the right: "A certain constellation of the sun-Earth-moon while the moon is observed by a person standing in different locations on Earth," and, on the left: "The moon orbits the Earth."

Mental images. Mental images are static mental representations of real or imaginary experiences of perceiving an object when the object is not actually present to the senses. Students may recall specific drawings they have seen (such as textbook drawings), or objects they have seen (the moon, as seen last night). Mental images are quite similar to mental models, but convey useful static information without the need for runnability. A summary of all knowledge pieces used in the current analysis is available in the Appendix.

External Resources: Visual Representations

An important external resource is physical drawings. Drawings work like mental models but operate in cases that are too complex to manage all the details internally. Additionally, drawings are conversational objects around which students can negotiate meanings. In cases where drawings provide the main anchor for an explanatory activity, they may play a significant role in shaping the conceptual dynamics of that activity: Once a drawing is constructed it becomes part of the conceptual dynamics; students refer to aspects of the drawing, gesture on it, draw attention to its details, and so forth.[ii]

Increasing the Resolution and/or Range of an Explanation

The present model attempts to describe the development of student understanding about the phases of the moon using visual representations. The two main constructs for describing this development are the *Resolution* and *Range* of the explanation (diSessa, personal communication). The progression from Explanation I to (the judged-to-be-better) Explanation II is regarded as increasing the *Resolution* of, and/or widening the *Range* of, the local coherence underlying the explanation.

Resolution. *Resolution* refers to the level of detail of information in an explanation. Students' applications of general schemas to mental models typically involve variable levels of *Resolution*. For example, a careless and casual application of a general schema to a specific mental model may lead to imprecise inferences while a more attentive-to-detail, and careful application may lead to more accurate inferences.

The following example from Gale, a fourth grade student,[iii] will help to demonstrate the construct of *Resolution*.

Example: Resolution of Explanation - What Causes the Seasons. Gale was asked to explain why there are seasons—why is it cold in winter and warm in summer? Gale was silent for a few moments and then said she just didn't know and had no idea. But suddenly she exclaimed, "AH!! I'VE GOT IT!" and drew an ellipse with one side closer to the sun and another side farther from the sun (Figure 2**Error! Reference source not found.**). She then explained: "When the sun is far away it is cold, and when it is near it is warm."

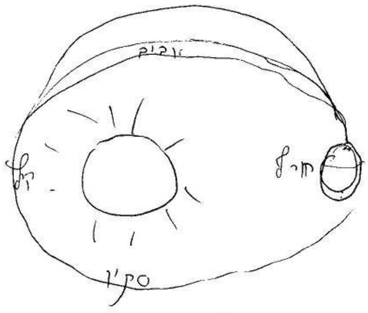


Figure 2 – Gale explains the seasons

This example demonstrates the potential for improving an explanation by increasing *Resolution*. Gale's explanation is common among children as well as adults. In this explanation a few knowledge pieces were cued:

- Proposition (based on common knowledge and direct experience): *It is cold in winter and warm in summer*.
- General schema: *Closer/Farther* (closer is stronger, farther is weaker);
- Mental model (enhanced by drawing): *The Earth moves in an elliptical orbit around the sun*.

This explanation seems to cohere and all the cued pieces fit together. However, the pieces fit together only at a low *Resolution*: The Earth is considered to be a point in space that orbits the sun, ignoring the fact that it rotates every day, and that different countries have different locations on it. If a mental model about the rotation of the Earth, as well as the effect of the sun on different countries facing the sun were considered, Gale could have said that: When the sun is far away it is cold in all countries, and when it is near it is warm in all countries. For whatever reason, however, she does not use that level of *Resolution* in this specific explanation. If she had, it might have cued a (potentially conflicting) proposition about different seasons occurring in different places on Earth, leading to the need to adjust the explanation.

Range. An explanation's *Range* refers to the extent or scope of the contexts that the explanation covers. A better explanation should account for as many contexts as appropriate. The same example of Gale explaining the causes of seasons will also help to demonstrate the construct of *Range*.

Example: Range of Explanation - What Causes the Seasons. Consider again the explanation, given by Gale: "When the sun is far away it is cold, and when it is near it is warm." When additional contexts are considered and new knowledge pieces are cued the collection of knowledge pieces might no longer fit together. Gale seems to consider in her explanation only the context of one specific country (probably the one she lives in). She does not consider other countries, and in fact, she does not acknowledge that there are different countries and any variation in seasons they may experience. She may or may not know that there are countries in which the seasons are opposite than what she experiences in her country. Even if she does know this factual information (either from experience or other indirect means) this piece of knowledge may not be available to her at this time. This piece can be introduced by an instructor or by a peer (for example, by mentioning a trip to South America, where the seasons are just the opposite of what we experience) and challenge the coherence of the lower-*Range* explanation. Her explanation would not be coherent anymore if she considers that the northern and southern hemispheres have opposite seasons. This would be a widening of the *Range* of explanation—from considering the context of one specific county, to considering many different countries.

Comparison with Thagard's (2000, 2007) model of explanatory coherence is helpful to clarify these two constructs. Thagard argued that scientific theories could progressively approximate truth if they increased their explanatory coherence by "broadening" and "deepening." Broadening refers to a theory's ability to explain more phenomena and new facts. Deepening a theory involves investigating the layers of causal mechanisms that explain why the theory works.

Thagard's "broadening" seems a close approximation to the current "increasing *Range*." However, the current "increasing *Resolution*" does not correspond to his "deepening." I did not find clear instances of "deepening" in the data, perhaps because my concern is with the progressive explanations of young students and not the paradigm shifts that are the main focus of Thagard's work. On the other hand, Thagard does not include the complementary idea of increasing *Resolution*. It is possible that scientists do always aim to account for all the detail available in current observations or conceptualizations. In any case, in the data corpus analyzed here, increasing *Resolution* does seem to play a critical role.

Summary of the Model

The model relates to the two focal questions. More advanced explanations, I am claiming, are characterized by a higher *Resolution* and/or a wider *Range* of coherence underlying the explanation. With regard to the first focal question—*How do we capture, in a realistically complex form, the conceptual structure behind students' explanations?*—the model suggests that a student's explanation is comprised of diverse types of knowledge pieces (propositions, general schemas, mental models, and mental images) that satisfy the student (i.e., they form a temporary coherent structure). The set of these activated knowledge pieces comprises an explanation with a specific *Resolution* and *Range* of coherence. With regard to the second focal question— *How do we Describe the Conceptual Dynamic Underlying the Progression of Explanations?*—the model suggests an underlying conceptual dynamic of the development of explanations as a progression of temporary coherent structures of activated knowledge pieces, whereas a more advanced explanation has a higher *Resolution* and/or a wider *Range* of coherence.

UNDERSTANDING THE PHASES OF THE MOON

The normative scientific explanation for the phases of the moon involves a combination of factors including:

1) Moon illumination (in a heliocentric frame of reference): The half-moon facing the sun is illuminated while the other half is dark (Figure 3, left).
2) Moon visibility from Earth (in a geocentric frame of reference): The half-moon facing the Earth is visible from Earth and the other half is not. In Figure 3 (center) the dashed line shows the visible and invisible parts of the moon as seen from Earth.

Figure 3 (right) shows the combination of moon illumination and moon visibility from Earth and how the illuminated part is seen from Earth.

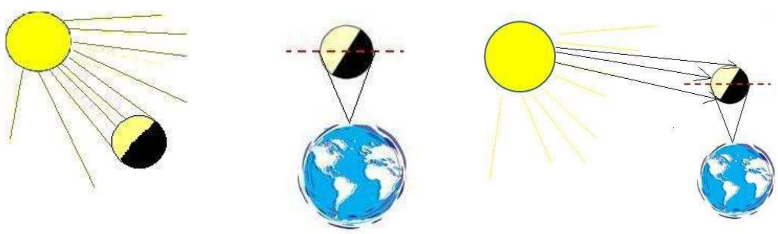


Figure 3 – What causes the moon's phases?

As the moon orbits the Earth it changes position (Figure 4, inner circle of moons). This change in position is insignificant compared to the vast distance between the moon and the sun (for space limitations the scale in the figure is distorted), therefore the moon is illuminated similarly regardless of its position. The dashed lines indicate the half of the moon that is visible from Earth and the half that is invisible. The visible half contains sections of both the illuminated half and dark half of the moon. An observer viewing the moon from Earth will therefore see different shapes of the moon (Figure 4, outer, numbered circle).

When the moon is in position 5, it is an interesting case because many people assume the Earth blocks the light from the moon (we will see this case in the analysis). In fact, the moon's orbit around the Earth forms a plane that is oblique to the plane formed by the three bodies: sun, Earth and moon. According to this geometry, the Earth usually doesn't block the light from the moon (only on some occasions, when a lunar eclipse occurs).

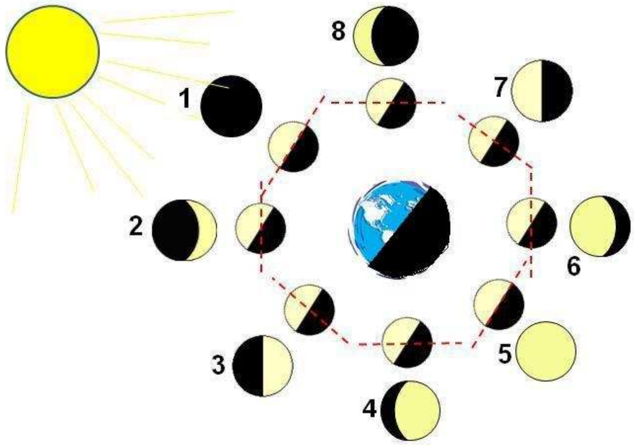


Figure 4 - Phases of the moon

As an instructional topic, the phases of the moon has attributes that make it an appealing choice for this research. Students have observed the moon's phases personally (direct experience), and many fifth and sixth graders have had some formal or informal science instruction related to the phases of the moon. Nonetheless, despite the familiarity, it is challenging for most children and adults to explain the phases of the moon adequately. First, a detailed examination of the moon can be more nuanced then only noting variance in shapes. For example, Plummer (2009) studied children in different age groups (Grades 1, 3, and 8) and their knowledge about apparent celestial motion, including the moon's apparent motion. She studied whether students notice the visibility of the moon during daytime, the path of the moon, its rising and setting point and so forth. Plummer discovered a greater accuracy and nuanced knowledge of apparent aspects of the moon's motion and appearance with increasing grade.

The greater challenge for older students as well as adults is explaining the causes of changing appearance of the moon. Students' difficulties understanding the phases have been extensively researched, and it is well documented that students provide all kinds of explanations for them (e.g., Sadler, 1987; Baxter, 1989; Barnett & Morran, 2002; Hansen & Barnett, 2004; Kavanagh, Agan & Sneider, 2005; Trundle, Atwood & Christopher, 2002, 2007; Hans, Kali & Yair, 2009).

Alternative explanations documented in the literature include the following:

- Moon phases are caused by clouds covering parts of the moon (Baxter, 1989).
- Moon phases are caused by the Earth casting a shadow on the moon (Baxter, 1989).
- Moon phases are caused by planets casting a shadow on the moon (Baxter, 1989).
- Moon phases are caused by the viewer's location on Earth; people in different geographic locations see different moon phases (Schoon, 1992; Trundle, Atwood & Christopher, 2007).

These alternative explanations, which are sometimes called conceptions, are regarded as fairly robust, difficult to change through teaching, and persistent, often to adulthood (Barnett & Morran, 2002; Baxter, 1989; Trundle, Atwood & Christopher, 2002; 2007).
A fair amount of the research literature on the moon's phases involves classifying student conceptions, analyzing patterns of statements following instructional interventions, and examining differences in understanding for different age groups. A common practice for studying trends of development is to develop codes for students' conceptual understanding, and then categorize students' responses based on the type of understanding the codes collectively reflect (e.g., Callison & Wright, 1993; Barnett & Morran, 2002; Trundle, Atwood & Christopher 2002, 2007). The coding approach is often useful for determining the effectiveness of different instructional interventions, though it stops short of describing changes occurring as student understanding develops.

Bearing this in mind, the present research proposes a model with a finer grained description of the structure of knowledge and its changes. The model suggests an explanation for why alternative conceptions seem robust, and offers a way of helping students reach a more scientific understanding of scientific phenomena.

METHOD

Data Collection

The present research is based on observing pairs of students age 10-14 (Grades 4-8) who generated representations while trying to explain and understand various scientific phenomena, such as the phases of the moon, sinking and floating objects, light and shadow, photosynthesis, air pressure, and energy transformations. Seven studies were conducted on the phases of the moon with pairs of students (total of 7 pairs of students). An in-depth analysis of one of those studies is reported as a case study in this paper.

The instructional design of these sessions consisted of four parts:

- Introductory activity – a brief (5-10 min) interview with the pair about the phases of the moon, the monthly cycle of the moon phases and the relationship between the moon, Earth, and sun, including their rotations on their axes and orbits. The interview usually ended with soliciting the students' explanations regarding the causes of the moon phases.
- Individual representation – each student drew a representation (diagram or sketch) explaining the phases of the moon.
- Collaborative representation – the two students share their representations with one another and explain the moon phases to each other using the representations. They then negotiate and co-construct a shared, consensual representation. This component usually lasts 30-45 minutes.

- Representation for presentation – the students produced a PowerPoint presentation of the phases aimed at explaining the phases to others. This stage sometimes involved a separate session a few weeks later.

There were several reasons to use pairs of students. First, it was essential to establish a relaxed atmosphere in order to promote meaningful, productive discussion. Second, students who work together express their thoughts verbally with no need for prompting. Third, interaction in pairs advances the development of explanations since, in some cases at least, students challenge each other and ask questions about their partner's explanation. The concept of students working in pairs added the challenge of a more complex analysis, which considers each student's conceptual understanding and the interaction between the pair.

During the sessions, my role as a researcher and as an instructor, included:

1. Facilitation – structuring sessions by introducing each component; inviting the students to perform the task; clarifying and elaborating where needed.
2. Intervention – while students performed the task (i.e., drawing explanations, explaining to each other, constructing a shared explanation, etc.), efforts were made to minimize my intervention. Still, interventions were needed on several occasions, and involved two types: 1. Research interventions – Asking students to clarify meanings in order to prompt explicit claims and reasons for later analysis. 2. Instructional interventions - instructional moves of the sort an instructor would make to enhance students' understanding, support their progress, or challenge their understanding if they seemed entrenched in a partial understanding. These interventions generally involved asking questions and conducting brief local discussions.

Sessions were videotaped and digitized for analysis and student representations were collected and scanned. Of the multiple studies conducted with pairs of students for this research, one study was selected as a case study, for demonstrating the application of the theoretical model.

Participants

The two participants in the case study were Rose and Natalie, two 11 years old (fifth grade students). They were recruited from a public elementary school, and volunteered to participate in the research. They were both considered to be good students. Rose and Natalie were good friends and used to working together. They were both very articulate and felt comfortable jointly discussing topics while listening and arguing points. Both were familiar with the term “phases of the moon” but could not recall if and when they studied it formally. Both recalled that the Earth takes one day to revolve on its axis, that the moon revolves around the Earth, and that the Earth revolves around the sun. When asked at the beginning of the session if they knew what caused the moon’s phases, neither could provide the normative scientific explanation.

Data Analysis

The data analysis follows the methodology of “knowledge analysis” (diSessa, 1993). Knowledge analysis is the joint study of the form and content of knowledge for the purpose of characterizing the architecture of knowledge and how knowledge changes. The main purpose is to generate and improve theories concerning learning by studying the form, content, and development of knowledge in a specific context in fine-grained detail, producing a moment-by-moment explanatory account of learning. Along these lines, the theoretical model presented in this paper was developed in order to model the fine-grain processes of knowledge reorganization and to highlight the issues of concern discussed above. The knowledge categories and knowledge pieces used in the present analysis are summarized in the Appendix.

The model presented here was developed through an iterative process involving phases of negotiation and application of the evolving theoretical model on datasets from multiple studies. The following analysis applies the evolving model to data from one case study.

A CASE STUDY – ROSE AND NATALIE EXPLAIN THE PHASES OF THE MOON

When the session began Rose and Natalie each had a different non-normative explanation of the phenomenon. When the session ended the girls had developed a shared, sophisticated explanation closely resembling the normative explanation. The next section examines the students' course in developing their explanation, detailing their reasoning and use of representations in this development, using the theoretical model described above. The analysis consists of six episodes, selected from two parts of the session—producing the individual representation, and producing a series of collaborative representations:

Episode 1 - An initial explanation by each student of the phases of the moon

Episode 2 - Each student considered and challenged her partner's explanation

Episode 3 - The students tried to integrate both their explanations

Episode 4 - Instructor's intervention aiming at greater *Resolution*

Episode 5 - Constructing a new explanation

Episode 6 - Increasing the *Range* and *Resolution* of the explanation.

Episode 1 – An Initial Explanation by Each Student of the Phases of the Moon

Initially, the students each produced a representation explaining the phases of the moon. On completing their drawings, each student was asked to explain the phases of the moon while referring to her representation. I first examine Natalie's explanation.

Natalie’s Representation and Explanation

Natalie drew a sequence of representations (Figure 5) of the moon-Earth-sun, slightly adjusting the position of the moon and the sun in each piece of the sequence. The drawing of Earth shows continents and perhaps countries.

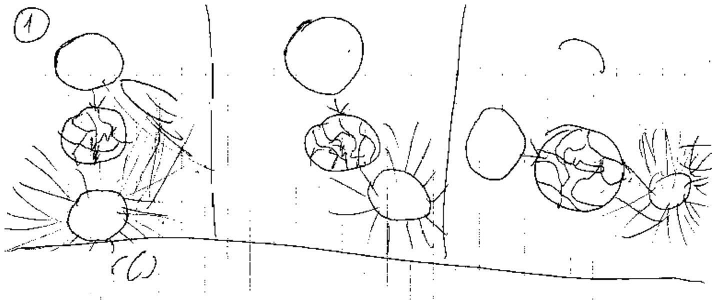
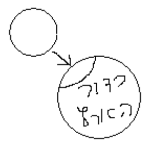


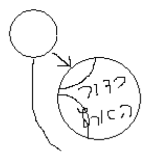
Figure 5 - Natalie's representation. In each drawing the sun is drawn with rays, the Earth is in the middle, with continents, and the moon is an empty sphere.

Next we see Natalie's explanation as she regenerates the drawing while explaining it to Rose. In all the following excerpts, snapshots of an evolving drawing appear alongside the transcript quotations. The snapshots were reproduced based on the video footage of how the representation was gradually generated.

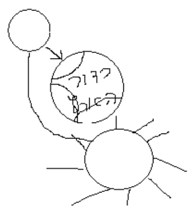
I think that like there is Earth *(Rose draws the Earth)* and the first time, say, the moon is here *(Natalie draws the moon),* and only this part of the Earth sees the moon *(Natalie draws an arrow, and an arc on the Earth, facing the moon),* and in this part it's like night now



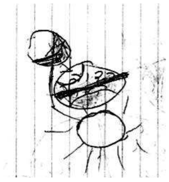
And this part sees less (*Natalie draws another arc on the side of the Earth, to represent another part of the Earth*)



This part *(draws another arc on the other side of the Earth),* this part doesn't see it [moon] at all, so in this part it's like there is day *(Natalie draws the sun),* it's sun,



And then in fact all this part we see, and it's like the day and night...."



As the above shows, Natalie's explanation focuses on the visibility of the moon from different locations on Earth at specific times of night and day. When standing in a location not directly facing the moon, the Earth blocks the moon, providing a partial view. The sun's role is somewhat incidental to explaining the actual phases, but is used to explain day and night.

Knowledge Pieces Activated in Natalie's Explanation

According to the presented theoretical model, Natalie's explanation was constructed using a collection of activated knowledge pieces (see Figure 6):

Mental images of the moon's shapes – In a brief conversation at the beginning of the session Natalie indicated familiarity with the shapes of the moon. Though one can reasonably assume that Natalie had mental images of the moon's shapes, it is difficult to infer the extent of the activation of specific images from her drawings and explanations.

Proposition: "The shape of the moon changes gradually over a month" – In addition to images of the moon shapes, experiential knowledge of the moon phases includes recognizing the sequence of gradual change from a new moon to a full moon and back again to a new moon.

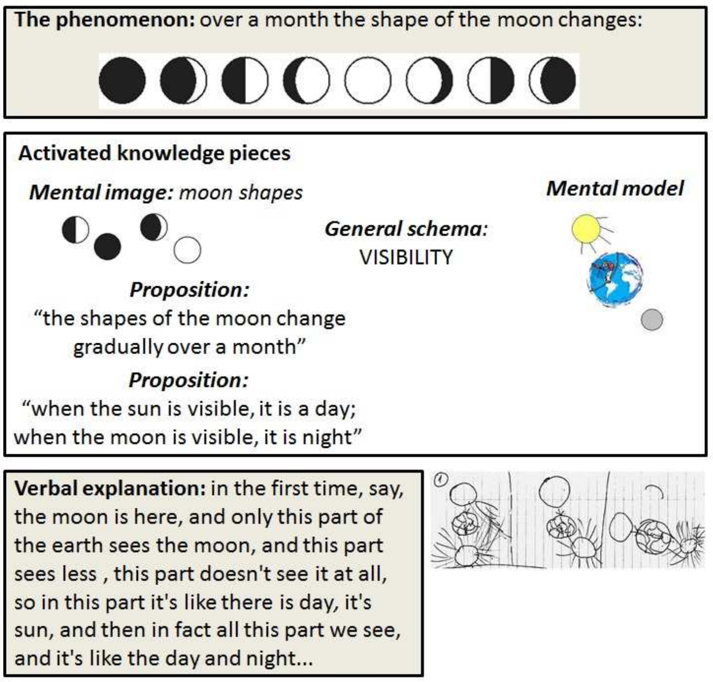


Figure 6: Construction of Natalie's explanation

Proposition: "When the sun is visible it is day; when the moon is visible it is night" – This is a familiar claim in our culture that is found in children's book illustrations, song lyrics, and stories. But in most of the cases I have examined, including that of Natalie and Rose, when this point was queried, the students admitted that the moon is occasionally visible during the day. Coincidently, the moon's position in her drawing is when the moon is visible at night and not visible during the day.

General schema: "Visibility" – an object's visibility depends on the observer's location. This general schema applies in different contexts: An observer gazing through his apartment window sees one part of the city while his neighbor next door sees another part. In the present context (in conjunction with the mental model described below), an observer standing on a sphere observing the space around him only sees the objects in front of him.

Mental model: "An observer stands on different locations on a sphere, watching the sun and the moon from these various locations." This model describes various configurations of the sun, Earth, and moon, and an observer looking at the sky from different locations on

Earth. In this case, there is a specific configuration where the Earth is situated between the sun and the moon. The general schema *Visibility* interacts with the mental model to produce inferences regarding how the moon and the sun, in this specific arrangement, are seen by the observer.

So, in shaping this explanation, Natalie used (at least) five knowledge pieces to form an explanation of the moon's phases: mental images of the moon shapes, a proposition about the gradual change of the moon shapes, the general schema of *Visibility*, a mental model of the observer on Earth watching the sun and the moon, and a proposition about day and night. Natalie seemed satisfied with her explanation and according to the model, the source of this satisfaction was the feeling that all activated knowledge pieces in the explanation fitted together.

It is interesting to note the knowledge pieces that were not cued: the mental models of the Earth's rotation on its axis and the moon orbit of the Earth were not cued even though Natalie indicated knowledge about them at the beginning of the session. Likewise, the mental image of a crescent moon in the blue sky in the middle of the day was not cued, even though Natalie explicitly mentioned this possibility in the conversation at the beginning of the session and also later in the session (as will be shown). These knowledge pieces (and possibly others too) were either not cued inadvertently or were not considered relevant to the explanation.

Resolution – There are two main reasons why Natalie's explanation demonstrated low-*Resolution*.

Let's consider the *Visibility* general schema in relation to the mental model. Running the mental model with this general schema would mean "moving an observer" around the sphere and inferring how the moon is visible to the observer from each location. If we run this mental model with the general schema carefully enough, we find that on the half sphere facing the moon, a full moon is visible from most of these locations. There is only a very limited set of locations from which the moon is partially visible. When these points are passed, the moon cannot be seen at all from half the sphere. The phases of the moon, according to Natalie's explanation, are observed from different locations on Earth, and are not distributed evenly, as shown in Figure 7.

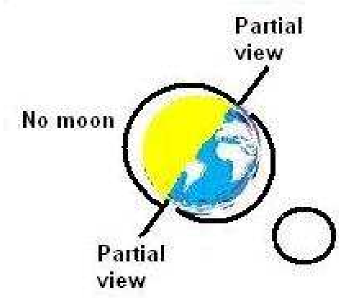


Figure 7: Phases of the moon according to Natalie's explanation

Natalie's explanation does not get into this level of *Resolution*, and she doesn't acknowledge this unique pattern. She does not examine how the partial views indicated by her reasoning actually mapped onto the moon's shapes. She only considered extreme landmarks such as the location right in front of the moon, out of sight of the moon, and somewhere between the two. All other locations were interpolated using these landmarks. If she had carefully mapped the resulted pattern to the moon's shape, this pattern might be puzzling to her, as it is inconsistent with facts that she knows (although these knowledge pieces may not be activated at this time), in the form of the following propositions: "The gradual change in phase is uniform over the month and can be noticed from one day to another"; and "During the day, the shape of the moon remains constant and change is unnoticeable." During the session it became clear that the propositions above were indeed part of Natalie's knowledge system. Applying the general schema onto the mental model with careful attention might have caused activation of these propositions, and hence a sense of incoherence and dissatisfaction.

Range: The *Range* of the explanation is also limited in that Natalie only considers one specific context where the Earth is between the moon and the sun. In this specific case, it is apparent that the moon can only be seen at night. In other cases, where the moon is positioned differently in relation to the sun and Earth, her claims about the appearance of the moon at night would no longer work.

Rose's Representation and Explanation

Rose's representation (Figure 8) was fairly similar to any standard textbook illustration of the moon's phases (see, for example, Figure 4): the sun shining on the moon and Earth and multiple moons drawn around the Earth. Rose appears to have adopted a textbook convention and attempted to infuse the familiar drawing with a meaning of her own. In contrast to textbook illustrations, in Rose's drawing the moon closest to the sun (position 1, in Figure 4) is a full moon and the moon farthest from the sun (position 5, in Figure 4) is a dark moon. Her drawing represents a common explanation that the moon phases are caused by the shadow cast on the moon by the Earth (e.g., Baxter, 1989).

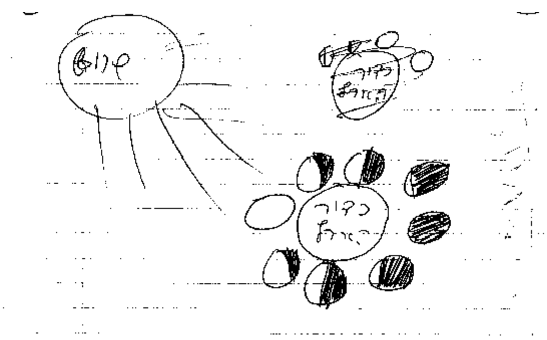


Figure 8: Rose's representation

When Rose explains her understanding to Natalie, she chooses to generate her representation again, explaining it as she draws. Her explanation is based on the idea that the dark phase is caused by the Earth blocking the sun rays from the moon:

(*Rose draws the sun and the Earth*) When the moon is here (*draws one moon on the other side of the Earth*),

Rose: the Earth entirely blocks the sun (*shades the moon*) and then the moon sort of doesn't get any light

Knowledge Pieces Activated in Rose's Explanation

The construction of Rose's explanation is based on a collection of activated knowledge pieces (see Figure 9).

Mental images of the shapes of the moon - Same as Natalie.

Proposition "the shapes of the moon changes gradually over a month" - Same as Natalie.

General schema: "Blocking"– An object can block the movement of another object - This general schema applies in many different contexts: for example, a ball rolling along the floor is blocked by a box and cannot reach the wall. Regarding the moon's phases, the blocking object is the Earth and the blocked moving object is the sun's light. In episode 2, Rose actually gestured to show the movement of light from the sun to the moon.

General schema "Illuminating" – a source of light shines on an object and lights the object's surface. This general schema was more apparent in episode 2, when Rose demonstrated how the sun's light illuminates parts of the moon. The general schemas *Blocking* and *Illuminating* work together in Rose's explanation.

General schema "More cause, More effect" – Rose used this general schema to explain the shapes of the moon for all phases except the completely dark phase. According to Rose, the moon's shapes are caused by the Earth blocking the sun's light from reaching the moon. The Earth blocks the sun's light and creates a shadow: More covering means more blocking.

Mental model – "The moon orbits the Earth in 30 days. The sun is stationary and the Earth also doesn't move during the time." – This mental model is applied with the general schemas *Illuminating* and *Blocking*.

Mental image of textbook illustration - Rose's conception of the moon phases may be associated with a textbook illustration she recalls. In a later conversation with Rose, she indeed acknowledged familiarity with the image from science books and said she had recalled it when asked to explain the phases. When Rose drew her representation, she adapted her design to other activated knowledge pieces. Her drawing of several moons around the Earth with different amounts of shading looked like the textbook illustration. However, the amount of shading and the resulted shapes were not precise. Potentially, this mental image has a high-epistemological status because science books tend to be considered trustworthy.

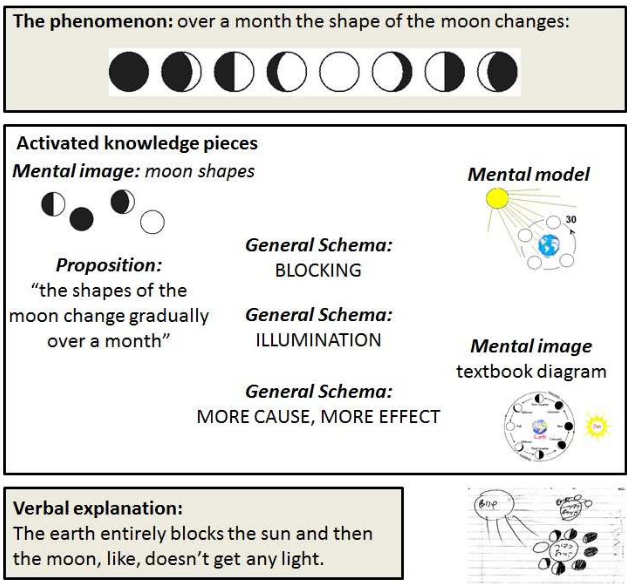


Figure 9: Construction of Rose's explanation

Resolution: Rose's explanation has low *Resolution*. When the general schemas of *Blocking* and *Illuminating* are applied properly to the model of the moon’s orbit, the moon’s shapes differ from those anticipated by Rose (Figure 10). For more than half the days of the month, light from the sun reaches the moon without being blocked at all by the Earth. The Earth only blocks the sun when it stands between the moon and the sun (fully or partially). Another inaccuracy is the shape caused by light being blocked when the Earth only partially blocks the sun’s light.

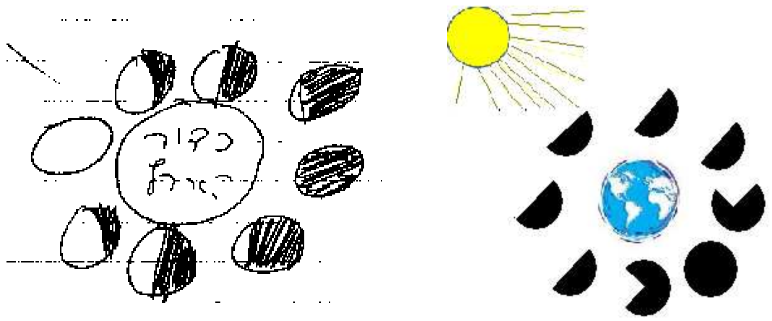


Figure 10: The phases of the moon inferred by Rose (left) and an accurate depiction of the phases carefully inferred by applying the general schemas and mental model used by Rose (right)

Instead of trying carefully to infer an accurate rendering of each of the moon’s shapes, Rose appears to rely on a (inaccurate) mental image (her recall of the textbook illustration) and the general schema *More cause, More effect*. As noted, this general schema implies that the more the Earth is in front of the moon the more light it blocks, and the less the Earth is in front of the moon the less light it blocks. When constructing her explanation, Rose apparently focused mainly on the dark phase, and the other phases were interpolated very loosely. In that sense, Rose demonstrated a similar inference pattern as Natalie, relying on central landmarks, interpolation, and an imprecise assessment of the schema’s application to each phase of the model.

Like Natalie, Rose did not use several knowledge pieces in her explanation, even though she knew them. These knowledge pieces consisted of mental models of the Earth's rotation on its axis and the orbit of the Earth and moon around the sun. Later, in reaction to Natalie's explanation, Rose was able to provide accurate descriptions of these models. But, for her explanation, she did not consider them as relevant.

Episode 2 – Each Student Considered and Challenged her Partner's Explanation

Rose, who had only reconstructed one moon, was about to draw additional moons around the Earth in order to explain other phases. Natalie stopped her, saying that Rose's explanation was (so far) exactly like hers:

Natalie So this is like…That's what I said, it's like the day, we have sun on the entire Earth almost, *(draws the semi-circle of the Earth facing the sun),* almost, and the moon, you can't see the moon

Except for this part *(illustrates the half circle facing the moon*), and there…

Rose: No, it's like, you cannot see the moon at all, it's dark (*swiping her open hand across the sheet, from the sun to the moon, showing that the Earth blocks the sunlight*).

Natalie: And what about other countries?

Rose: There are nights where you can't see the moon at all.

Natalie showed Rose that the moon Rose had drawn was also the "dark phase" in Natalie's explanation. The two girls assigned different meanings to the dark moon in their drawings: According to Natalie the moon is dark when "the-moon-is-not-within-the-observer's-field-of-view," whereas in Rose's account "the-moon-appears-dark-because-no-light-reaches-it." Natalie explains that Rose's moon cannot be seen from a location facing the sun but can be seen from locations on the other side of the Earth. To support her claim, she highlights the two sides of the Earth—the side that does not see the moon and the side that sees it. Rose disagrees and says that in the situation Natalie has drawn, the moon cannot be seen even on the other side of the Earth because it is dark.

When Natalie asks about other countries, she has good reason. Her explanation is constructed on the basis of the moon's visibility from different locations on Earth. Thus, at any given moment, some countries will see the moon while others will not. This is not congruent with Rose's claim that there are nights when no country can see the moon at all.

To clarify her standpoint, Rose decided to complete her explanation, which Natalie had interrupted earlier. She drew seven more moons around the Earth. As she drew, she constructed her explanation, gesturing to each moon, and describing how the sun's light travels past the Earth and reaches the moon, shading the moon accordingly. Hence, the moon in position 5 is fully shaded, the moon in position 4 is mostly shaded, the moon in position 3 is partly shaded, and the moon in position 1 is fully lit (similar to Figure 8). While Rose was drawing and explaining the appearance of the different phases, Natalie watched and listened to Rose's explanation. Then she paused for a second and said:

> "No. … if we just take one, just take one moon now…"

Natalie wished to focus on just one moon and the areas of Earth from which it is visible or not, similar to how *she* draws the situation. To do this, she makes a strong move, covering all the new moons Rose had drawn, leaving only the original moon uncovered (Figure 11):

> "Say we take… what was the first one? Say, let's take this one (*placing her hands on the representation and hiding the other moons*)"

Figure 11: Natalie hides the other moons

This gesture helped to refocus the girls on what was important to Natalie in the explanation: the moon, sun, and two sides of the Earth. She repeated her explanation but this time also drew a line dividing the Earth in half—one half facing the sun and the other facing the moon:

Natalie: So, here in fact, this whole part of the Earth… (*pointing with her finger to the half facing the sun and drawing a line dividing the Earth*) is day and this whole part is night.

Natalie: So, if in this part there is night (*points to the half of Earth not facing the sun*), we need to see the moon, because this is how it will be every day, the moon will not be seen on the other part of the Earth.

Natalie continued arguing, following the same line of reasoning, that when the moon cannot be seen from one region of Earth, it can be seen from the other, and that this happens every day. Rose, unaware of Natalie's different basis for explanation (the moon's visibility from different locations on Earth), thinks that Natalie is mistaken because she does not take the moon's revolution around the Earth into account. In the following excerpt, Rose tried to get Natalie to consider the moon's revolution:

Rose: No, but the moon revolves *(gesturing with her pen in circles*). When the moon is here *(pointing to position 3)* we see only half, when it's here *(pointing to position 4),* we see it like this, when it's here *(pointing to position 5),* we see it…do you understand?

Natalie: So that means that one day we see the moon and one day we don't see the moon

Rose: Not one day we do and one day we don't. It takes a month *(gesturing with her finger in circle around the Earth and counting the moons)* one, two, three… 8 days.

Natalie: (*Silence of 3 seconds*) so every 8 days we won't see the moon?

Rose: (*Laughing*) okay, 30 days.

Natalie: Okay. It's not such a big difference…

Rose explained that the moon revolves around the Earth and that a different shape is visible depending on where you are. Natalie, applying Rose's idea into her explanation, inferred that we see the moon every other day, which is contrary to our experience. Quite certain about her explanation, Rose explained how the phases change in a month.

After several more exchanges, the discussion drew to an end and I asked if the girls had agreed on their explanations. Rose said they had agreed, presumably believing she addressed all Natalie's "difficulties." Natalie was silent, presumably not feeling in agreement at all. I suggested that they had quite different explanations. Rose replied:

"Let's put it this way: we can take the two drawings and combine them…"

Rose and Natalie's Activated Knowledge Pieces

In this episode, Rose and Natalie adhered to their initial explanations using the same activated knowledge pieces as initially (see Figure 6, Figure 9). Rose's initial drawing (before drawing the other moons) resembled Natalie's drawing and when each looked at the drawing they saw different aspects of it. On the one hand, their focus is influenced by their activated knowledge pieces. On the other hand, the knowledge pieces are reactivated and stabilized by the details of the representations the girls attend to.

One should note the role of the drawn representations in the space shared by the two girls in this discussion. The girls discuss the differences in their understanding with reference to Rose's drawing. Their arguments are based on relatively stable explanations, and they respond to one another's pointing and gesturing on the drawing.

Natalie’s explanation was based on the moon’s visibility from different locations on Earth. She argued that the moon is not visible from the side of the Earth facing the sun and that this is the phase when the moon is not seen. On that date, she maintained, the moon can still be seen from locations on the other side of the Earth. She highlighted the two sides of the Earth—the side that does not see the moon, and the side that sees it (Figure 12). This highlighting may have been aimed at shifting Rose's attention and communicating these ideas to her.

Figure 12: Natalie's highlighting

Rose attempted to shift Natalie’s attention by using gestures on the drawing as she explained. She swiped her hand across the sheet from the sun to the moon, to show that the Earth was in the way and blocking the light from the moon. Later, after Rose drew seven additional moons, Natalie focused their attention on one of the moons by covering all the others. Natalie also added another line to divide the Earth into two parts, the part that sees the moon and the part that does not.

The *Resolution* and *Range* of the students’ explanations is the same as in Episode 1—their explanations have not changed yet.

In the next episode, the students try to combine their explanations.

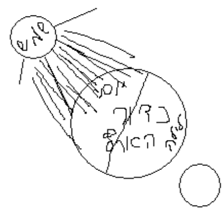
Episode 3 – The Students Tried to Integrate Both Their Explanations

Adopting Rose’s suggestion to combine the two drawings, the girls, for the first time in the session, generated a collaborative, new representation: They took the activity from personal-sense-making in episodes 1 and 2 to integration and consensus-seeking in episode 3. In this new undertaking, Natalie was open to considering some of Rose's ideas, and, seeing that, Rose became less critical than before.

Natalie began the explanation by incorporating one of Rose's previous ideas: When the moon is in position 5, the Earth blocks the sun's light, and no light can reach the moon. Immediately after, she added her idea about the visibility of the moon. Rose's cooperation in producing the drawing based on Natalie's instructions is evidence of a temporary agreement or at least a gesture of collaboration.

Natalie: Put the moon here. (*Rose draws the moon on the other side of the Earth*). No light reaches it now at all.

Natalie: The sun lights only one side of the Earth (*pulls the paper and turns it around, draws many lines from the sun to the Earth. Rose tries to add something to the drawing, but Natalie pushes her away politely*). Now let me show you (*pulls the paper and begins to draw*)… lights on one side of the Earth. On this side it is, like, day, and they can't see the moon. (*Rose divides the Earth and writes: "day" and "night")*

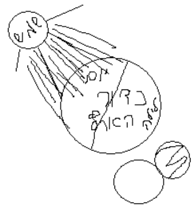


Natalie: The whole other side of the Earth is like, [Rose: Night]… it is other countries, In Israel, the days, like, it can't be that now in Kefar Saba[iv] it is night.

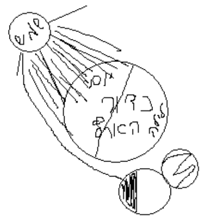
Natalie explicitly noted "No light reaches it (the moon) now at all," acknowledging Rose's idea of the Earth preventing sunlight from reaching the moon by blocking it. Then, she immediately started reasoning about the visibility of the moon as before. She explained that the section of the Earth facing the sun (day) cannot see the moon. Rose followed this idea by drawing a line across the Earth and adding the words: "day" and "night."

In the following excerpt, Rose adds another moon close to the first one, as in her original explanation. Natalie attempts to integrate their ideas with reference to the new position of the moon:

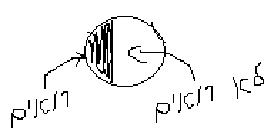
Rose: So, say, now I'll put it here (*drawing a second moon just next to the first one*)



Natalie: So that a tiny bit of light reaches here, *(draws a single ray from the sun to the moon)*, say to here, *(shading a small area of the moon*) and then on this day, they can see this…



Natalie: (*Rose writes "visible" on the shaded side, and "not visible" on the non-shaded side*) look, and then on that day the US (further from the sun) sees this, as if there is only a little bit of moon,



Natalie: And then when it gets closer *(draws a third moon to the left of the second one)*, the US will see it more *(shades one part of the new moon)*, and also we are going to see it half because it is closer to us *(points to the area facing the sun)*, and the sun reaches it. The sun will not reach this part *(points to the non-shaded segment of the new moon)* and it will reach this part *(points at the shaded area of the moon)*, but half of the US will see and half we will.

Natalie: This is how we can also see the moon during the day *(Rose nods)*; there are days when we can see it

With a clear grasp of Rose's reasoning, Natalie explained why some of the light from the sun reaches the moon and why the moon is partly shaded. She then combines the idea of a partially shaded moon with that of the moon's visibility in different locations to explain how this moon shape can be seen in different countries. After that she considers other positions of the moon and continues reasoning about the moon's shading and why this shape can be seen in both the U.S. and Israel.[v] Natalie's reasoning does not lead to a conclusion regarding which pattern of moon shapes is eventually formed.

Natalie's Activated Knowledge Pieces

Since Natalie is more active in this episode, the following analysis focuses on her reasoning. Natalie began to integrate some of Rose's ideas. Although the model of the moon's orbit around the Earth was not previously activated in constructing her explanation, she now considers it. After Rose drew a second moon, Natalie applied three general schemas—*Visibility*, *Blocking*, and *Illuminating*—to two mental models (Figure 13).

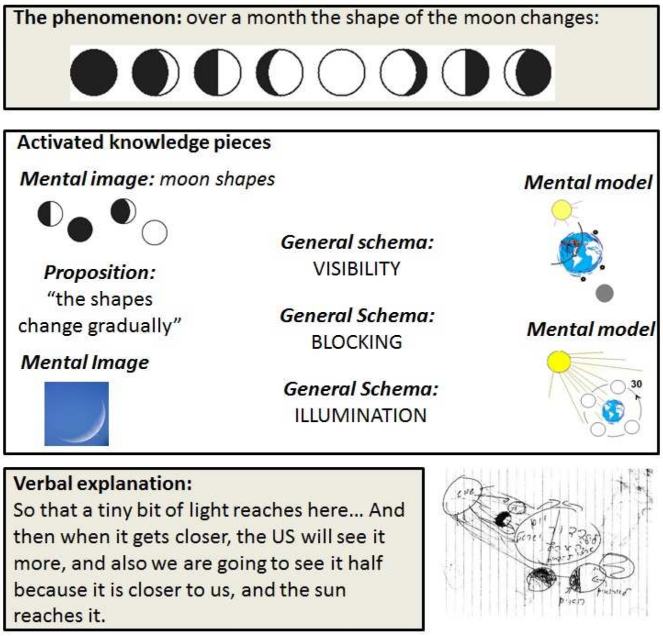


Figure 13: Natalie's activated knowledge pieces used in producing the integrated explanation

This complex application, which arose from the students' need to combine their ideas, generated a complex explanation but did not provide details of each phase's appearance in each part of the month. Therefore, the explanation is still low in *Resolution*, since the pattern of phases produced by applying the general schemas to the mental models is not clearly articulated and is an incomplete description of the phases of the moon.

The *Range* of this explanation is wider than in Natalie's original construction as it considers multiple positions of the moon and enables her to envisage the moon being visible not only at night but also during the day. In contrast to the single moon she initially drew, by drawing the moon in several positions around the Earth, Natalie construes that the moon can be also visible from locations on Earth facing the sun. Where her previous reasoning did not activate this mental image of a crescent moon in a clear blue sky, the current context does activate it.

Episode 4 – Instructor's Intervention Aiming at Greater Resolution

Given the students' apparent satisfaction with their shared representation and explanation, I added another moon to their drawing (Figure 14) between the sun and the Earth (position 1) and asked them what the observer would see at this phase.[vi] The question sought to elicit a careful application of the general schemas to the particular context of the moon in that specific position in an attempt to increase the *Resolution* of the explanation. By focusing on this position in particular, I sought to highlight the imprecision with which the general schema of *Illuminating* was applied to the mental model of the moon's orbit.

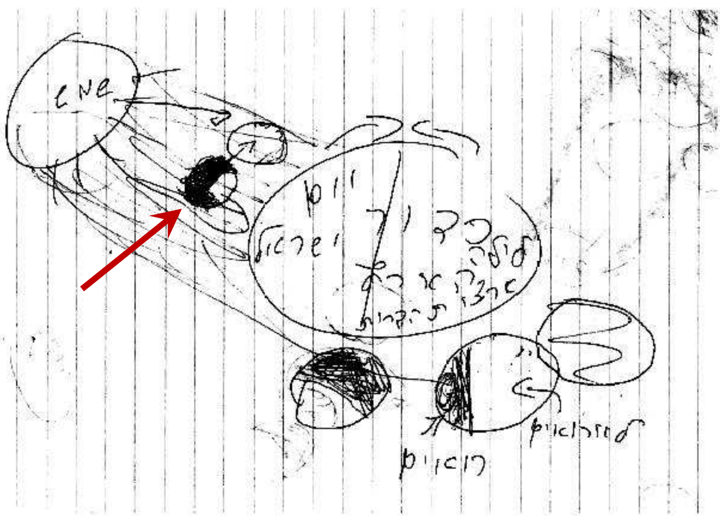


Figure 14: How does the moon appear when in this position? (Moon indicated by arrow)

Rose quickly responded that in this position the entire moon is visible.

OP: What is seen here?

Rose: When the moon is there so, (*sweeps open hand from sun to moon showing the direction that light would travel*), we see all of it. Right? Because the sun lights it.

Natalie agreed with Rose, but adds that the moon is only visible in Israel. Rose objects and introduces the Earth's rotation on its axis. This is the first time anyone has mentioned the Earth's rotation on its axis:

Natalie: So we can see all of it from Israel

Rose: Right…No! From Israel, and also, I think, from the United States. Because the Earth also rotates around, remember that!

Rose: So, when this arrives here (*draws another moon just next to OP's moon, and adds an arrow to show movement*), these two (*the two halves of the Earth*) will switch and the United States will see it when it's here (*points to the moon she has just drawn*)

Natalie's and Rose's Activated Knowledge Pieces

At first, Rose responded very confidently to my question. Applying the *Illuminating* general schema imprecisely, she explained that in this phase, since nothing blocks the sun's rays from reaching the moon, the moon is fully lit. This particular answer is congruent with the structure of activated knowledge pieces (Figure 9) forming her explanation: First, there must be a full moon somewhere, since a full moon is seen once a month (mental image of the moon shapes). According to the pattern of the gradual change of the moon in her drawings (see Figure 8), the full moon occurs when the moon is in position 1. The textbook illustration, when recalled vaguely, suggests a similar pattern as well.

Natalie's brief comment about seeing the full moon in Israel gets Rose to sharpen the *Resolution* of her explanation. Natalie's comment prompts (for Rose) the activation of a new mental model—the rotation of the Earth. Rose applied the general schema of *Visibility* to this mental model in an attempt to inform Natalie why the full moon is visible from all countries around the world on the same day. The mental model of the Earth's rotation on its axis had not been cued thus far—she only considered daily occurrences not occurrences *during the day*. By incorporating this new knowledge piece, Rose increased the *Resolution* of her explanation.

Natalie's brief interjection on the visibility of the full moon from Israel revealed that she clearly still retained her earlier explanation which placed most emphasis on the general schema of *Visibility* focusing on the moon's visibility/lack of visibility from Earth. She did not respond to Rose's elaboration of her explanation and stayed silent.

Following Rose's response that the moon in position 1 is a full moon, the students and I began to explore how the sun or any other source of light illuminates a sphere. We explored with flashlights and balls what the students had previously explored on paper, namely the illumination of one object (the moon) by a source of light (the sun). That discussion is not reproduced here, however, the process of carefully exploring how objects are illuminated is an example of increasing *Resolution*. Part of the reason that Rose's initial explanation was low in *Resolution* was an imprecise application of the *Illuminating* and *Blocking* general schemas on a mental model. The current exploration is meant to refine the ability of applying these general schemas with more attention and precision.

Episode 5 – Constructing a New Explanation

The discussion in episode 4 regarding the illumination of an object by a light source ended in agreement that in position 1, the only part of the moon that is lit is the part facing the sun, while the part facing the Earth is dark.

As soon as she grasped this, Rose excitedly exclaimed that this was the opposite of what she said before. This she repeated three times over the next 50 seconds:

"Ah! So it's the opposite of what I said"

"So wait, it is the opposite of what I said before!"

"So, wait a minute, it seems to me… it seems to me, that it is more or less what I said, only the opposite. Here now it is like, dark *(points to position 1)*, and here it is light *(points to position 5)*."

In order to construct an explanation based on Rose's latest understanding, the girls needed to clarify some details. Therefore, Rose and Natalie began a new drawing, reformulating their explanation of the phases. In this episode they sought to demonstrate that the phase in position 5 was not the dark phase (as indicated in their prior explanations), but the full moon phase as implied by their new understanding that the moon was in its dark phase in position 1. They sought sensible ways of showing that the moon in position 5 is illuminated by the sun even though the Earth apparently blocks it. Unaware of the evidence that the sun, the Earth, and the moon are not always perfectly aligned, they offered tentative explanations about how the light from the sun bypasses the Earth and reaches the moon.

Natalie began to draw, saying that this time she would use "normal sizes" (Figure 15). She drew the Earth, and divided it down the middle, marking the locations of Israel and the U.S. She drew the sun and commented that the sun is much larger than the Earth.

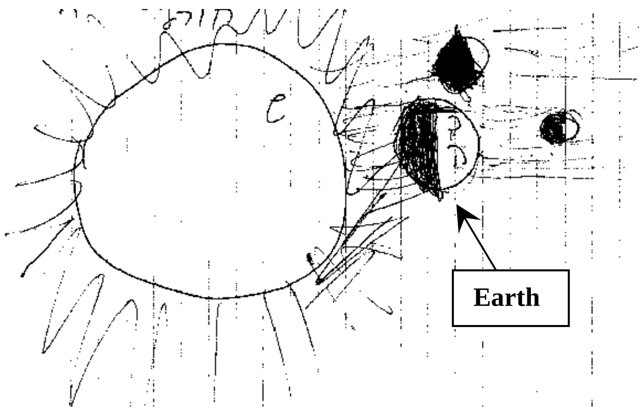
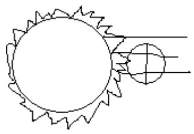


Figure 15: A new representation with some new ideas

The girls then added the moon in position 5 and Rose explained that because the sun is not flat, but round: the sun rays are able to go around the Earth and reach the moon:

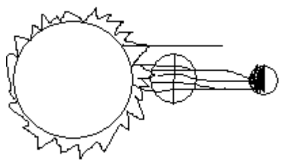
Rose: The sun is not flat, it is round. What I said is, say, *(puts her hand rounded on the sun)* [Natalie: yes, I got it, I got it… *(begins to draw)*] So, they can reach the moon.

Natalie: So, the sun's rays exit and enter (*draws lines that cross the Earth and reach the moon*).



Rose: And they go above and reach the moon (*with her hand she mimes the sun's rays going around the Earth and reaching the moon*)

Natalie: Right. But they (the rays) light up… which part do they light up? They only light this part *(colors the half-moon facing the sun)* [Rose: yes, right] that's why we see only the part that is lit…



Rose: Yes! So it is exactly the opposite of what I said before! *(smiles)*

Natalie: Right!

Rose's and Natalie's Activated Knowledge Pieces

Rose was excited to learn that the moon phase in position 1 was the dark phase and not the full-moon phase. Her excitement was doubtless partially due to the new discovery's comfortable fit with most of the activated knowledge pieces in her explanation—specifically the mental image of the textbook illustration, which probably had high epistemological status. Even though the details of the girls' drawing might have changed, at this stage the design as a whole still resembled the textbook illustration. Thus, to Rose, not having to challenge what she already "knew for certain" was satisfying and excited her very much.

The new proposition that evolved from the exploration in the previous episode—“the moon in position 1 is the dark phase”—is also epistemologically high-status because it was perceived as the outcome of collaborative thinking and facilitated by an authority (teacher/researcher). Indeed, Rose and Natalie tried hard to fit this proposition into the explanation. The general schema *Blocking* was replaced by the general schema *Bypassing*, and the girls used this new general schema (*Bypassing*) to show how the moon in phase 5 is illuminated. Obviously, the girls lacked scientific knowledge on how light travels and the geometry of the sun-Earth-moon system.[vii]. But it was interesting to see their efforts to use what they knew to fit the pieces into a consistent explanation.

Another knowledge piece that was activated was the general schema *Visibility*. It was used by Natalie in this episode not only to indicate which region of Earth sees the moon, but exactly what part of the moon can be seen: “They light only this part (*colors the half-moon that faces the sun*) [Rose: yes, right] that’s why we see only the part that is lit…” It is evident now that both Rose and Natalie employed general schemas that they had used before, but in slightly different ways, and combined them to form the new explanation (Figure 16).

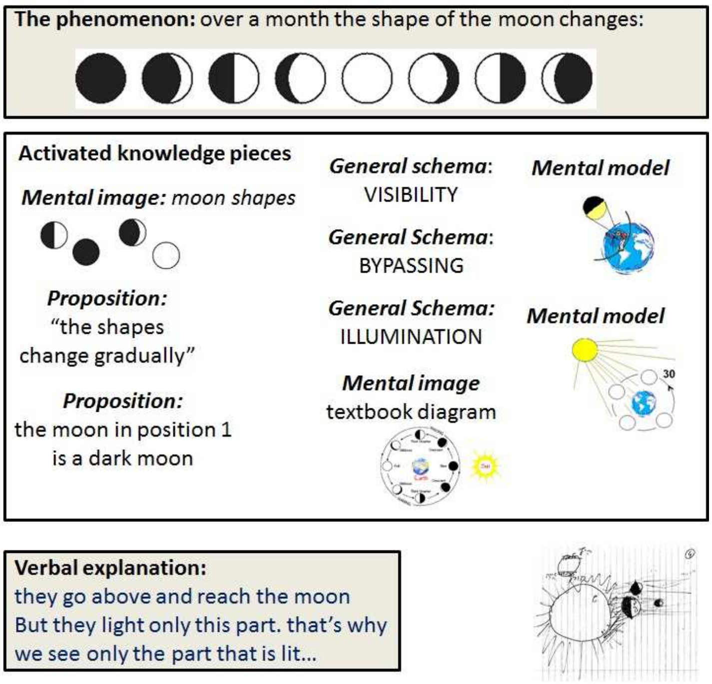


Figure 16: Knowledge pieces which Natalie and Rose activated while generating the new explanation

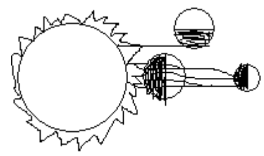
Rose, who had felt very confident about her previous explanation involving the obstruction of sun rays, apparently had no difficulty abandoning it. What seems more important to Rose than retaining her previous explanation was aligning the new explanation with high-priority knowledge pieces such as the mental image of the textbook illustration.

Episode 6 – Increasing the Range and Resolution of the Explanation

In this episode, I suggested adding other positions of the moon to the drawing to introduce a still wider *Range* of contexts. Natalie drew another moon in position 7 (Figure 15, upper moon). For several seconds, the girls considered which part of the moon the sun would illuminate. The inaccurate scale of the drawing distorted the illuminated and dark areas of the moon.

Natalie reconsidered the moon in position 5 and suggested a more detailed explanation of this phase and its transition to the next phase:

Natalie: So, now that this is lit (*coloring the part of the Earth facing the sun*) then also this is lit (*coloring the part of the moon in position 5 facing the sun*) and only the U.S. sees it. We don't see the moon during the day, usually… and now, when the moon (*points to the moon in position 5*)…



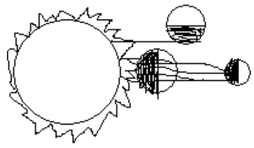
Natalie: (*turns to me*) What turns around faster, the moon or the Earth?

Natalie is again reasoning about how the moon is seen from different locations on Earth. When she considers what happens when the moon moves, the relative rotations and revolutions become relevant and activated in her reasoning: "What turns around faster, the moon or the Earth?" The question of the relative cycles of the Earth's rotation on its axis and the moon's orbit around the Earth arose several times during the session preceding this episode, when Rose raised the point and explained it to Natalie. However, this is the first time this piece of knowledge became relevant and active for Natalie.

Rose was happy to provide Natalie with this information about the moon's orbit and the Earth's rotation on its axis. For Rose, these pieces of knowledge had been relevant through most of the session and this was not the first time she had tried to explain it to Natalie; she was happy to explain it again: "Look, Natalie, it takes the Earth one day to rotate around its axis, and it takes one month for the moon to orbit the Earth."

This time, Natalie sees this as a necessary piece of knowledge and she proceeds with her explanation, still related to phase 5:

Natalie: If it is lit here (*covers the part of the Earth not facing the sun*), when it (the Earth) rotates, this is lit (*points to the countries located across from the sun*)



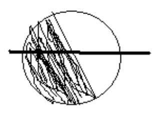
Natalie: So here it is light, and the moon hasn't moved yet, it will only revolve in a few days. So, this is why we see a little bit of the moon during the day, *(recoloring the part of the moon in position 5*), for several hours, not for the whole day, because this (the Earth) rotates (*forms circles around the Earth*)

Rose: Okay, it seems to me that we both understand.

Natalie has worked out what Rose has understood in episode 4: that the same moon in seen in all countries on the same day. Natalie's inference is slightly more complex than Rose's since she also incorporates day and night into the explanation.

I again encouraged the girls to talk about additional phases. With some help Natalie re-shaded the moon in position 7 more appropriately to show the part of the moon facing the sun that receives sunlight. Rose provided the following explanation:

Rose: So we… what we actually see is this part *(drawing a line almost perpendicular to the shaded part)*, more or less…



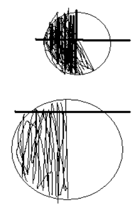
Natalie has an insight following Rose's elaboration of which part of the illuminated moon is visible:

> Natalie: Ah! One moment, (*takes Rose's hand off the representation*) the moon doesn't really get larger and smaller, it's simply what we see. We only see the illuminated part [Rose: Right!] (*Natalie colors the illuminated part again*), and now it's only half of it, and it's possible that if we look before… so maybe we will only see this part. This line here [Rose: Right]. It depends (*glanced at OP*) on when we look and… when the moon...

This was Natalie's "Aha" moment, when she understood that the moon does not really increase and decrease in size because we only see parts of it, but that what changes is the shape of the illuminated part seen from Earth. She summarized this as a combination of "when we look" (*Visibility*) and "when the moon" (its *Illumination*).

Rose reiterated the same ideas and combined the conception of the moon's illumination and the Earth observer's perspective of the moon more explicitly:

> Rose: So, in fact when the moon is here this part is lit (*shading again the half-moon facing the sun*), and the Earth, say, this part (*draws a line on the Earth representing the field of view*) sees relatively this part (*draws a line segmenting the moon – the line is parallel to the line she drew on the Earth*) – something like that – of the moon, that's lit.



> Natalie: That is why we see it… These are the phases of the moon!

Rose uses lines creatively to emphasize her unified conceptualization. She colors the half of the moon that faces the sun and leaves the other half blank to indicate illumination. She then draws a line that divides the moon area which lies parallel to a line representing the observer's perspective. The half-moon facing the Earth is the part seen by the observer.

Rose's and Natalie's Activated Knowledge Pieces

This explanation, which was developed gradually through the careful examination of multiple details, approximates the normative explanation. It explains the illumination of the moon by the sun and the visibility of the moon from Earth. Although each girl emphasizes certain ideas over others (e.g., Natalie emphasizes day and night on Earth), they mostly share and agree on this collaborative explanation. Figure 17 displays the knowledge pieces activated in their explanation.

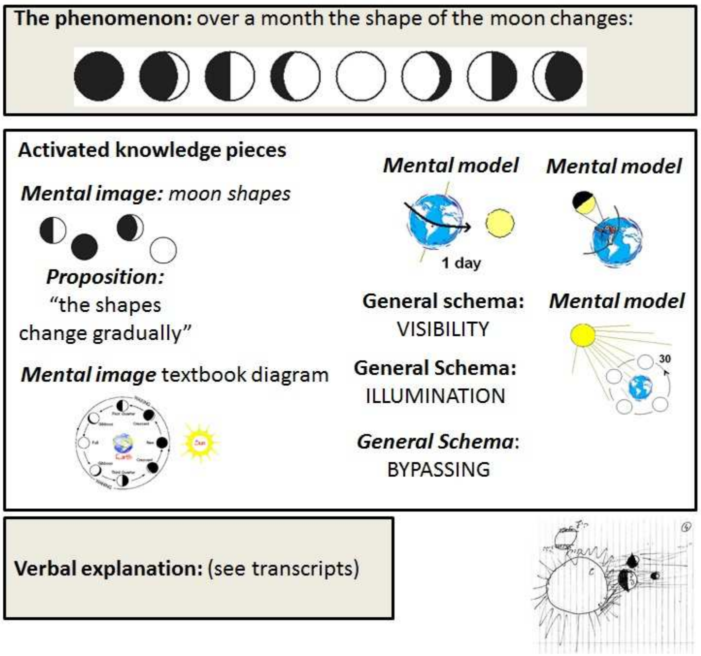


Figure 17 - Rose and Natalie's final explanation

To attain the final explanation both Natalie and Rose needed to adapt their reasoning regarding the problem. Rose had to reapply the general schema of *Illuminating* to the mental models differently in order to fit the new proposition that the moon in position 5 is a full moon. In the final explanation, Rose no longer applies the general schema of *Blocking*, but does apply *Bypassing*. Additionally, the general schema of *Visibility* becomes relevant for

Rose and she applies it to the mental model of an observer on Earth observing the moon in different positions to determine which part of the moon is seen in each position.

Natalie carefully examines the application of the general schema of *Visibility* to the mental model of the moon's orbit of Earth. By considering the effect of the moon's movement to a new position, the relative rotations and orbits become relevant to her reasoning and activated: "Which turns around faster, the moon or the Earth?" This was the first time Natalie activated this knowledge piece.

When the girls considered other moon phases, they tried to infer the precise appearance of each phase. They utilized the representation and added details to it to help them see how the moon appears from Earth by shading the non-illuminated part and indicating the visible part. The girls found it easier to deduce how the moon would appear from Earth in positions 1 and 5 and no representational aids were needed. But, in different positions, a more concerted effort was required. This was a clear case where increasing the *Range* of explanation (examining more phases) also increased *Resolution*: A more elaborated idea about how exactly the moon is seen from Earth as a combination of the moon illumination and the visibility from Earth. The *Resolution* of their explanation is now high, as they apply very carefully and attentively the various general schemas on the various mental models. The *Range* is wide as well, as they now consider a variety of positions of the moon around the Earth.

DISCUSSION

Rose and Natalie demonstrated a marked development in their explanations and understanding of the phases of the moon. The two students entered the process with two different explanations of why the moon changes shape. Their initial explanations were low in *Resolution.* Natalie's explanation was also narrow in *Range.* When the session ended, they had reached a shared, high *Resolution* and wide *Range* explanation. This explanation also happened to be very similar to the scientific explanation of the phases of the moon. Let us revisit some of the critical milestones in this process.

Rose and Natalie began the session with two different explanations, constructed on the basis of activated knowledge pieces that cohered with low *Resolution*. Natalie applied the general schema of *Visibility* to a model of different locations on Earth and a particular configuration of sun, Earth, and moon; Natalie applied this general schema only roughly without carefully examining the pattern that evolves and how it is mapped out on the actual phases. The *Range* of Natalie's explanation was also limited in that Natalie only considered one specific position of the moon, a specific case where the moon can only be seen at night. Rose, producing a different explanation, applied the general schemas of *Blocking* and *Illuminating* to the model of the moon orbiting the Earth. She applied the general schemas to the model and generated—partly inferring, and partly interpolating—the shapes of the moon when it is in different positions relative to the Earth. The pattern of moon shapes resulting from the imprecise application of the general schemas to the models was congruent with the mental image of the shapes and their sequence, and also with a rough mental image of textbook illustrations of the phases of the moon.

When the students shared their explanations with each other it was apparent that the explanations were very different and that each student preferred her own explanation. Neither explanation was seriously challenged by the other. Natalie explained her drawing and was not challenged at all by Rose. Rose explained her drawing and assumed that Natalie's arguments arose from lack of understanding. They sought to integrate their explanations at my request to collaborate on a shared explanation. They worked hard on this and did quite well, however, the resulting pattern of the shapes of the moon remained somewhat unclear and the coherence was loose.

A more substantial development followed my attempt to trigger an increase in *Resolution* by highlighting a particularly problematic context (*Range*): namely, what exactly happens when the moon is in position 1? The question led to a detailed exploration of how a sphere is illuminated by a source of light. This was an example of a careful examination of how exactly a specific general schema (*Illuminating)* applies to a mental model—which is the essence of increasing *Resolution*.

The detailed exploration of how a sphere is illuminated revealed that in position 1 the moon is actually seen as a dark moon rather than a full moon (as Rose had earlier inferred) and in position 5 (the phase they had mainly been reasoning about and had initially conceived as the dark moon) was actually a full moon. This demonstrates nicely how the expectation of coherence drives the construction of explanation: In order for phase 5 to be a full moon and fit the pattern of moon phases (and textbook illustration) the students needed new knowledge pieces to explain it. By applying the general schema of *Bypassing* along with *Illuminating* and *Visibility* they could explain how phase 5 could be a full moon. The explanation they found was detailed and the knowledge pieces fitted together with relatively high *Resolution*, for positions 1 and 5.

At this point, I again asked the students to explore other positions of the moon. This request was aimed towards widening the *Range* of the explanation, so that it includes other positions of the moon. Exploring other positions of the moon involved finding nuanced ways of applying the general schemas to the mental models and provided increased *Resolution*. For example, when the moon is in positions other than position 1 or 5 it is challenging to infer the shape of the moon viewed from Earth. The students very carefully explored the moon's illumination and visibility from Earth in these other positions, making innovative use of their drawing. They ended up with an explanation that had both high *Resolution* and high *Range* coherence.

Let us now discuss some of the important issues highlighted in the analysis, by referring again to the two focal questions raised earlier.

1. How Do We Capture, in a Realistically Complex Form, The Conceptual Structure Behind Students' Explanations?

The analysis described the structure of the students' knowledge as a complex system. Students exhibited a wide diversity of context-sensitive fine-grained knowledge pieces, including propositions, general schemas, mental models, and mental images. This level of detail was essential for capturing knowledge resources and their reorganization into productive roles in more advanced explanations.

Let us compare Natalie's activated knowledge pieces in episode 3 to the activated knowledge pieces playing out in their final explanation, in episode 6 (Figure 18).

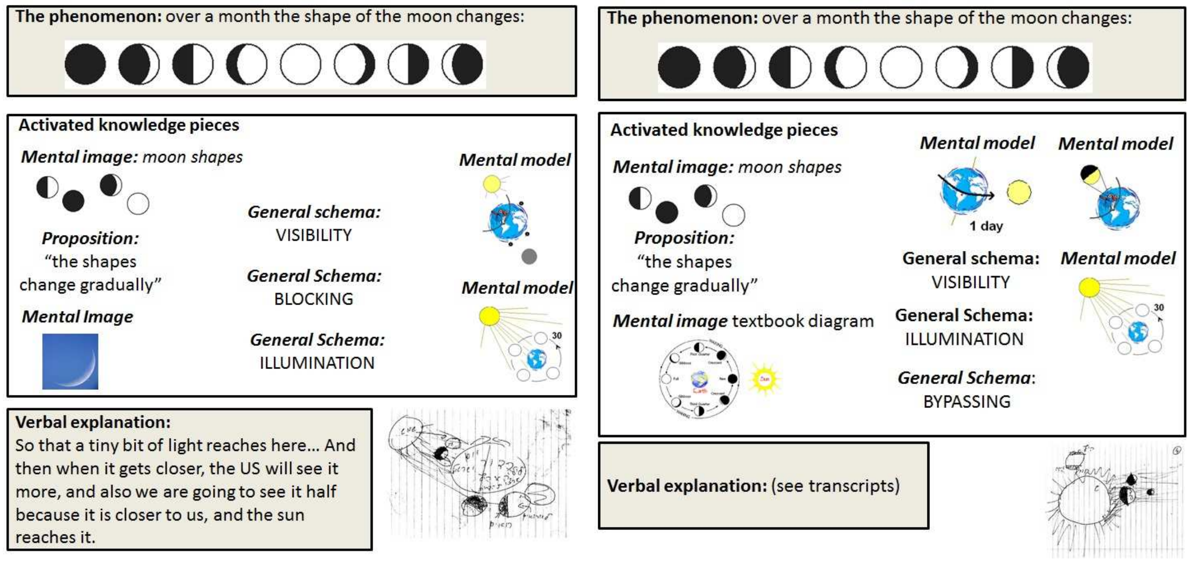


Figure 18 - Natalie's activated knowledge pieces in Episode 3 and the joint activated knowledge pieces in Episode 6

Both the *Visibility* and *Illuminating* general schemas were activated in both explanations. However, in episode 3, the *Visibility* general schema was applied to a mental model where an observer observes the moon and sun from different locations on Earth. This application only considered whether the object (sun or moon) is visible from a particular location, and not which part of it is visible. Inferring the part that is visible involves a more careful application of the general schema on the mental model. In episode 6, the general schema of *Visibility* was applied to a slightly different mental model. This mental model involved an observer from a specific location on Earth observing the moon in various positions. The general schema of *Visibility* as now applied allowed the students precisely to infer how the moon is viewed from this location.

The general schema *Illuminating* was also applied in episode 3 to the mental model of the moon's orbit around the Earth. But whereas in Episode 3 this application was imprecise, in episode 6 the students applied the general schema very carefully to infer the illuminated and dark parts of the moon in each position.

In episode 6, the general schema of *Blocking*, used by the students in episodes 1-3, is considered irrelevant to the situation and the students use instead the general schema *Bypassing*. Scientifically, light does not "bypass," and this general schema applies to other phenomena such as waterways, gas, masses of people, and so forth; it does not apply to light. What the students were missing was a fact concerning the geometry of the lunar system. The moon's orbit around the Earth is an oblique plane to that formed by the sun, moon, and Earth. According to this geometry, the Earth does not normally block the sunlight from the moon (apart from the rare occurrence of a lunar eclipse). That piece of information could have helped the students, but at this point was not available to them.

The analysis shows that there were hardly any new pieces of knowledge underlying the advanced explanation. Only the organization of knowledge pieces was different. The students' intuitive knowledge exhibited continuity and productiveness throughout the development process. Furthermore, the students' explanations were compiled from conceptual resources that are neither right nor wrong, although it is possible to apply them appropriately or inappropriately: General schemas from one explanation can be applied more precisely to a mental model, or applied to different mental models to provide a more adequate explanation.

These findings have implications with regard to the differences between the “knowledge-as-theory” and “knowledge-in-pieces” perspectives. A common assumption within the science education community is that students’ understanding involves alternative robust conceptions that pose an obstacle to them when learning school science. Described in these terms, one could say that, initially, the two students entertained common “misconceptions.” In fact, their initial explanations are documented in the literature: (a) “the phases of the moon occur due to the shadow cast on the moon by the Earth” (e.g., Baxter, 1989); (b) “the different phases of the moon are seen from different parts of the Earth” (e.g., Schoon, 1992). The current analysis suggests that students’ understanding is constructed from finer-grained pieces than the grain-size of a misconception. Decomposing misconceptions into smaller knowledge pieces enables a researcher to observe the re-organization of these components into a more advanced understanding. Beyond the theoretical implications of these findings, this observation has important instructional implications. The central message is that instruction should nurture students’ intuitive ideas rather than strive to replace them by correct scientific knowledge. Some directions for how to lead students towards more adequate knowledge building are pointed to in the next section.

2. What is the Conceptual Dynamic Underlying the Progression of Explanations?

The analysis supports the idea that students construct explanations that feel coherent. That feeling is linked to the way activated knowledge pieces—specifically epistemologically high-status pieces—fit together. Moving from one explanation to a more advanced explanation is not done by convincing the students (either by convincing each other as in episode 2, or by an instructor), but by directing them toward more rigorous exploration of relevant details and contexts.

In every explanation, activated knowledge pieces may fit together but with differing *Resolution* and *Range*. As the details gradually get refined, knowledge pieces that were activated earlier no longer fit together and it is necessary to reorganize the knowledge pieces so that they fit together again, in a higher *Resolution* and/or a wider *Range*.

Increasing *Resolution* and/or *Range* often did not happen voluntarily by the students. I, as an instructor, had an important role in focusing on fruitful directions from among the many available options. For example, by focusing on what happens in position 1, the students undertook a thorough examination of how exactly the sun illuminates the moon thus considerably improving the resolution. Later, I encouraged the students to explore other positions (improved explanation *Range*), and this careful exploration led to still greater *Resolution* enhancement.

When details are explored by increasing *Resolution*, reorganization can take place, as happened here. The students do not need to be convinced that a different explanation is better than their own, and instead, they reconstruct a new explanation through the process of increasing *Resolution*. When Rose and Natalie realized that the moon in position 1 is observed as a dark moon and not a full moon, they needed to fit this new knowledge piece with their other activated knowledge pieces, which led to a reorganization.

Once the students could give a precise account of how the general schemas applied to the mental models for both simple and more complex phases they could grasp the bigger picture. In one example of this, Natalie realizes the underlying reason why the phases of the moon occur:

> "Ah! One moment, (*takes Rose's hand off the representation*) the moon doesn't really get larger and smaller, it's simply what we see. We only see the illuminated part [Rose: Right!] (*Natalie colors the illuminated part again*), and now it's only half of it, and it's possible that if we look before… so maybe we will only see this part. This line here [Rose: Right]. It depends (*glanced at OP*) on when we look and… when the moon..."

The central claim—that the development of students' explanations and understanding is a function of increases in the *Range* and/or *Resolution* of explanations—is significant for at least two reasons.

The first is a theoretical significance: The "knowledge-in-pieces" perspective argues that students' intuitive knowledge gets reorganized through the process of learning and conceptual change. The current analysis demonstrates such a moment-by-moment learning process. But, in addition it also identifies two mechanisms that drive improvements in explanations: increasing *Resolution* and widening *Range*. Of course, these concepts and the theoretical model offered here were developed through an iterative analysis of a small sample of cases and applied in detail to a single case study; further research needs to be done to examine the applicability and efficacy of these two mechanisms in other learning contexts.

The second reason is practical. *Resolution* and *Range* provide productive direction for instructional interventions. While it is premature to offer much detail here, this is briefly discussed below.

CONCLUSIONS AND INSTRUCTIONAL IMPLICATIONS

DiSessa (2008) argued that even if we are convinced that people have global "models" or "conceptions" (the conceptual change community has yet to agree on this, see diSessa, Gillespie, & Esterly, 2004), we still need to know how to disassemble those entities into fine-grain pieces, to trace how new ideas are built. The model developed in this paper suggests a way to understand the organization of fine-grained knowledge pieces that make up a student's explanation and trace the reorganization of these pieces as explanations develop.

The model has similarities to Sherin et al.'s (2012), which describes the conceptual dynamic of students' explanations during clinical interviews. Sherin et al. conceive a dynamic process in which all explanation constructions are temporary mental states which can change rapidly from one moment to the next when different knowledge pieces are cued.

In the sessions conducted in the current research, students usually progressed through a series of explanations involving growing sophistication and sometimes also approximation to the scientific explanation. This progression can be attributed to the instructional design of the sessions, which is quite different from a clinical interview: In a clinical interview, the goal is to study aspects of the interviewee’s knowledge and there is no explicit attempt to support the interviewee’s learning. In some cases, the interviewees develop their understanding through this interaction but there is, by no means, a specified learning goal, and the interaction does not support such a goal. The session analyzed in this paper (like other sessions in this research) was a learning session where the students were expected to try to make sense and improve their understanding. Occasionally, my interventions resembled an instructor’s more than an interviewer’s and my questions were geared to provoking the students’ thinking to support their progress.

The students’ explanations in this research were not only verbal, but embedded in tangible, drawn representations. Visual representations retain the record of earlier explanations and conceptualizations. The fact that visible representations are depicted on a stable and physically shared medium may affect the nature of the conceptual dynamic. For example, the instructor’s accessibility to the shared visual representations that can be observed, pointed at, and accounted for provided fertile ground for generating issues of *Resolution* and *Range*. Future research may elucidate the special role of visual representations in this regard.

The model presented here also has instructional implications for engaging student ideas and facilitating a type of learning that continually moves from intuitive understanding to sophisticated understanding. Instead of being offered, or convinced to adopt, a better explanation, students constructed their own explanations, exploring details, extending their limits, and in this process, finding their own ways to reconfigure and improve their explanations. The fact that there was a continuity of ideas may explain the relative ease with which Rose and Natalie transitioned to new explanations and their lack of resistance to this. Although the session lasted a long time, there was no sense of confrontation or any need to convince or persuade the students to choose the new explanation over the old one.

This would seem to support the position that productive instructional interventions should have the intention of increasing the *Resolution* or widening the *Range* of students' own explanations. Offering students a "better" explanation—the normative explanation—without attending to the conceptual resources the students have "at hand" is unlikely to lead to real understanding. Recall Natalie's changing interactions with the piece of information regarding the Earth's rotation and the moon's orbit. In the explanation that she constructed herself (in episode 2) this piece of information was completely irrelevant. However, once it became productive within a specific context and particular construction (in episode 5) she used it meaningfully. The model developed in this research suggests productive directions of supporting students in developing their intuitive conceptual understanding and increasing its sophistication.

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REFERENCES

Barnett, M., & Morran, J. (2002). Addressing Children's Alternative Frameworks of the Moon's Phases and Eclipses, *International Journal of Science Education.* 24, 859.

Baxter, J. (1989). Children's understanding of familiar astronomical events. *International Journal of Science Education, 11*, 502.

Callison, P, L. & Wright, E, L. (1993) *The effect of teaching strategies models on Preservice elementary teachers' conceptions about Earth-sun-moon Relations.* Paper presented at the Annual meeting of the National Association for Research in Science Teaching, Atlanta.

Carey, S. (1985). *Conceptual change in childhood.* Cambridge, MA: MIT Press.

Carey, S. (1999). Sources of conceptual change. In E. K. Scholnick, K. Nelson, S. A. Gelman & P. Miller (Eds.), *Conceptual development: Piaget's legacy* (pp. 293–326). Mahweh, NJ: Erlbaum.

Craik, K. (1943) *The Nature of Explanation*. Cambridge: Cambridge University Press.

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10* (2–3), 105–225; responses to commentary, 261–280.

diSessa, A. A., Gillespie, N., & Esterly, J. (2004). Coherence vs. fragmentation in the development of the concept of force. *Cognitive Science, 28*, 843-900.

diSessa, A. A. (2002). Why "conceptual ecology" is a good idea. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 29–60). Dortrecht, Netherlands: Kluwer.

diSessa, A. A. (2006). A history of conceptual change research: Threads and fault lines. In K. Sawyer (Ed.), *Cambridge handbook of the learning sciences* (pp. 265-281). Cambridge, UK: Cambridge University Press.

diSessa, A.A. (2008). A bird's eye view of 'pieces' vs. 'coherence' controversy. In S. Vosniadou (Ed.), *Handbook of conceptual change research.* Mahwah: Erlbaum

Gentner, D. and Stevens, A.L. (1983). *Mental Models*. Lawrence Erlbaum Associates Inc.

Susan Haack (1993), *Evidence and Inquiry*, Oxford, UK: Blackwell

Hans, M., Kali, Y. & Yair, Y. (2009). Added Value of Integrating Computerized and Physical Models for the Development of Learners' Spatial Abilities with regards to the moon Phases. In Y. Eshet, A. Caspi, S. Eden, N. Geri and Y. Yair (eds.) *The learning man in the technological era, Proceedings of the Chais conference on instructional technology research*, Open University Press, Israel. (Hebrew)

Hammer, D., Elby, A., Scherr, R. E., & Redish, E. F. (2005). Resources, framing, and transfer. In J. Mestre (Ed.), *Transfer of Learning from a Modern Multidisciplinary Perspective* (pp. 89-120). Greenwich, CT: Information Age Publishing.

Izsák, A. (2000). Inscribing the winch: Mechanisms by which students develop knowledge structures for representing the physical world with algebra. *The Journal of the Learning Sciences*, *9*(1), 31-74.

Johnson-Laird, P.N. (1983). *Mental Models: Towards a Cognitive Science of Language, Inference, and Consciousness*. Cambridge: Cambridge University Press.

Kapon, S., & diSessa, A. A. (in revision). Reasoning through instructional analogies.

Kavanagh, C., Agan, L., and Sneider, C., 2005, Learning about Phases of the moon and Eclipses: A Guide for Teachers and Curriculum Developers: *The Astronomy Education Review*, Volume 4, p. 19–52.

Kuhn, T. S. (1962/1996). *The Structure of Scientific Revolutions*. Third Edition. The University of Chicago Press, Chicago.

Nersessian, N. J. (1989). Conceptual change in science and in science education. *Synthese 80*(1), 163–183.

Nersessian, N. J. (2002). Maxwell and "the Method of Physical Analogy": Model-based reasoning, generic abstraction, and conceptual change. In: *Essays in the History and Philosophy of Science and Mathematics,* D. Malament, ed. 129--166. Lasalle, Il: Open Court.

Özdemir, G. and Clark, D.B. (2007). An Overview of Conceptual Change Theories: *Eurasia Journal of Mathematics, Science and Technology Education,* v. 3, p. 351-361.

Parnafes, O. (2007). What does fast mean? Understanding the Physical World through Representations. *The Journal of the Learning Sciences. 16*(3). 415-450.

Pfundt, H. and R. Duit. (2009). *Bibliography: Students' Alternative Frameworks and Science Education.* Kiel, Germany: University of Kiel Institute for Science Education.

Plummer, J. D. (2009). A Cross-age Study of Children's Knowledge of Apparent Celestial Motion, *International Journal of Science Education, 31*:12, p. 1571-1605

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*(2), 211-227.

Roschelle, J. (1992). Learning by collaborating: Convergent conceptual change. *The Journal of the Learning Sciences, 2*(3), 235-276.

Sadler, P. M. (1987). Misconceptions in astronomy. In *Proceedings of the Second International Seminar on Misconceptions and Educational Strategies in Science and Mathematics* (pp. 422–425). Ithaca, NY: Cornell University

Schoon, K. 1995, The Origin and Extent of Alternative Conceptions in the Earth and Space Sciences: A Survey of Pre-service Elementary Teachers, *Journal of Elementary Science Education*, 20, 503.

Sherin, B., Krakowski, M., & Lee, V. R. (2012). Some assembly required: How scientific explanations are constructed in clinical interviews. *Journal of Research in Science Teaching.49*(2): 166-198

Smith, J. P., diSessa, A. A., & Roschelle, J. (1993). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *Journal of the Learning Sciences, 3*(2).

Strike, K. A. & Posner, G. J. (1990). A revisionist theory of conceptual change. In R. Duschl & R. Hamilton (Eds.), *Philosophy of science, cognitive science, and educational theory and practice*. Albany, NY: SUNY Press.

Thagard, P. (2000). *Coherence in Thought and Action*. Bradford Books.

Thagard, P. (2007). Coherence, Truth, and the Development of Scientific Knowledge. *Philosophy of Science 74* (1):28-47.

Trundle, K. C., Atwood, R. K., & Christopher, J. E. (2002). Preservice elementary teachers' conceptions of moon phases before and after instruction. *Journal of Research in Science Teaching*, *39*(7), 633-658**.**

Trundle, K. C., Atwood, R. K **& ,.**Christopher, J. E. (2007). Fourth-grade elementary students' conceptions of standards-based lunar concepts. *International Journal of Science Education*, *29*(5), 595-616**.**

Vosniadou, S., & Brewer, W. F. (1992). Mental models of the Earth: A study of conceptual change in childhood. *Cognitive Psychology*, *24*(4), 535–585.

Vosniadou, S. & Brewer, W.F. (1994). Mental models of the day/night cycle. *Cognitive Science*, *18*, 123-184.

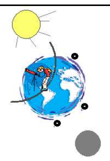
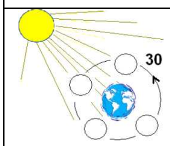
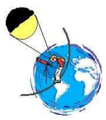
Vosniadou, S. (2008). *Handbook of conceptual change research.* Mahwah: Erlbaum

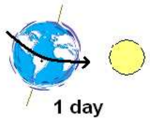
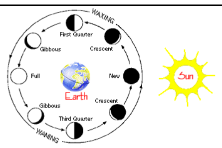
Vosniadou, Vamvakoussi, & Skopeliti, (2008). The framework theory approach to the problem of conceptual change. In S. Vosniadou (Ed.) *Handbook of conceptual change research.* Mahwah: Erlbaum

Wagner, J. F. (2006). Transfer in pieces. *Cognition and Instruction*, *24*(1), 1-71.

Wiser, M. (1988). The differentiation of heat and temperature: History of science and novice-expert shift. In S. Strauss, (Ed.), *Ontogeny, phylogeny, and historical development* (pp. 28–48). Norwood, NJ: Ablex.

Appendix – Knowledge Elements Appearing in the Analysis

Knowledge element	Type	Description
VISIBILITY	General scheme	An object's degree of visibility varies according to the location of the observer.
BLOCKING	General scheme	An *object (A)* can block the movement of another *object (B).*
ILLUMINATING	General scheme	A source of *light (A)* shines on an *object (B)*, and lights the object's surface.
BYPASSING	General scheme	An *object (A)* can bypass an *object (B)* in order to reach an *object (C).*
MORE CAUSE, MORE EFFECT	General scheme	The effect of a certain factor is increased by the extent of that factor.
	Mental model	An observer stands on different locations on a sphere, watching the sun and the moon from these various locations.
	Mental model	The moon orbits the Earth in 30 days. The sun is stationary and the Earth also doesn't move during the time.
	Mental model	An observer stands on one location on a sphere, watching the moon in various positions.

	Mental model	The Earth rotates on its axis in one day.
Moon shapes 	Mental image	Mental images of various shapes of the moon.
	Mental image	A mental image of a textbook illustration of the phases of the moon.
	Mental image	A mental image of a crescent moon seen during the day.
"The shapes of the moon change gradually over a month"	Proposition	
"When the sun is visible, it is day; When the moon is visible, it is night"	proposition	
"The moon in position 1 is a dark moon"	proposition	

[i] These categories are borrowed from an early version of Sherin, Krakowski, & Lee (2012).

[ii] One of the main goals of this research was to examine the effect of the use of visual representations on the process of developing understanding. However, this question is beyond the scope of the current paper and besides mentioning it briefly in this section, I will leave the substantial discussion for a future paper.

[iii] This short study was an independent study, unrelated to the focal case study of this paper.

[iv] Kefar Saba is a small town in Israel, close to where Natalie and Rose live.

[v] Israeli students are very familiar with the time difference, especially between Israel and the US. Many students visited the US (Rose lived in the US for several years), and if not, they usually have friends and relatives, and they are aware of the time difference for planning phone conversations and alike.

[vi] The moon that I added was blank. The shading is from a later state, after they figured out the light and shadow on the moon. This happened after this episode ended. However, Figure 14 is a scan of the final state of the representation.

[vii] The moon's orbit around the Earth forms a plane that is oblique to the plain formed by the three bodies: sun, Earth and moon. According to this geometry, the Earth usually doesn't block the light from the moon (only in some occasions, when a lunar eclipse occurs).