Models and Modeling in Science Education

David F. Treagust
Reinders Duit
Hans E. Fischer *Editors*

Multiple Representations in Physics Education

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Foreword

Progress on Multiple Representations

As an abstract subject, physics is fundamentally represented in mathematical language, and physicists use mathematical modelling to predict the behaviour of natural systems. To develop physics research, and to teach physics, in addition to abstract representations such as formulas and graphs, there has been a long tradition of using concrete representations such as physical models and analogies as explained by Richard Feynman (1994) in *Six easy pieces*. Indeed, the main purpose of these external representations is to discuss results to develop research in physics and enable conversations about physics concepts in teaching and learning. Nevertheless, these representational transformations can also lead to significant problems in the learning process when a particular representation might add or leave out information and therefore might change the meaning of other representations used to explain a certain concept.

The research presented in the three sections of this book is introduced in Chap. 1 which argues that teaching and learning physics involve mentally working with multiple external representations. This mental work is described by various psychological theories which are applied in different ways for designing physics teaching and learning in classroom settings. Part I (Chaps. 2, 3, and 4) addresses specific multiple representations at different levels of the education system and with different physics topics and their effect on learning. When multiple representations are used for teaching, the expectation is that they should be successful for students in their learning. To ensure this is the case, the effect of those implementations on student learning as well as on classroom communication should be investigated. Such an approach is relevant for representations used in all topics of physics teaching at all levels of the school system and is also important for computer-based representations.

Part II (Chaps. 5, 6, 7, 8, and 9) highlights the relationship between students' and teachers' interpretation of different representations and their use and own creation of representations on different levels of abstraction. Using a specific representation to explain a certain physics concept can cause learning difficulties even when the same kind of representation is used for another concept. As a consequence, an appropriate approach to improve learning is the construction of representations by the learners themselves explicitly taught and assisted by the teacher. Evaluating representations and making them useful for learners require all representations to contain the essential aspects of the underlying physics concepts.

In Part III (Chaps. 10, 11, 12, and 13), the focus changes from the nature of the representation to students' abilities needed to use or apply these representations. The research explores how students' competencies are used to relate different representations to each other to enable conceptual development through argumentation. Furthermore, the challenge of teaching and learning physics is illustrated by the claim that representations have to work on isomorphic problems of different topics. Interpreting representations across different physics topics requires students to use their abilities to explain and assimilate the representations accordingly. Similarly, virtual interactive textbooks may provide help or guide students to work with multiple representations.

As well as reporting research studies, this book offers examples of instruction that may help researchers and practitioners in physics education to plan and reflect upon their own physics teaching from the perspective of multiple representations. External representations are fundamental for understanding abstract physics concepts, and I congratulate the editors and the authors in bringing these different studies together as a volume in this series. For physicists, physics teachers and physics educators, there is much to learn here about the nature of multiple representations and how they can be used to guide teaching and assess learning in physics.

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Alexander Kauertz

Reference

Feynman, R. P. (1994). *Six easy pieces.* Reading: Helix Books.

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Chapter 1
Multiple Representations in Physics and Science Education – Why Should We Use Them?

Maria Opfermann, Annett Schmeck, and Hans E. Fischer

1.1 Introduction

Imagine you are teaching physics at high school and you want to make your students familiar with the concept of block and tackle. Would you do so by just explaining in a verbal fashion, for instance how the length of the pulling rope or the number of strands relates to the pulling force? Probably not – after a demonstration with a real tackle you might most likely show students exemplary pictures of different situations with tackles (cf. Fig. 1.2), point at certain parts of the pictures and by doing so, explaining the concept to your students. In this case, you would already make use of multiple representations – (spoken) words and pictures. The reason for doing so is very obvious. Many concepts, processes or relations can be comprehended much more quickly when some kind of picture is provided because pictures are able to show at once what would take much longer to be described with words or demonstration experiments. Furthermore, students are able to visualize the rather abstract contents of physics topics being taught such as with the block and tackle. Moreover, when using multiple sources of information, learners are able to choose those sources with which they prefer to learn, in this case the real tackle or the pictures.

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Another reason for using multiple representations in physics teaching is the structure of physics itself. Physics uses mathematical modelling to describe phenomena and to explain relations between variables. Therefore, teaching and learning physics necessarily includes both the conversion of physics modelling into mathematical modelling (e.g., regarding functional relations) and the interpretation of mathematical models from a physics point of view (cf. Bing and Redish 2009; Nielsen et al. 2013). Newton's law of gravity, for example, can only be understood and applied to different problems when the functional relation is used in a mathematical form. But for instance in schools, the consequences for the behavior of physical objects and their predictability are often presented verbally. In addition both modes, the verbal and the mathematical, need graphs following mathematical rules but expressing physical meaning.

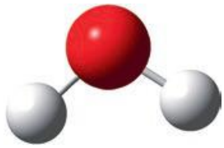
Therefore in physics, more than only one representational format is often used to convey information and support knowledge construction. Accordingly, and developed not only for teaching physics, a number of well-established theories claim that the use of multiple representations can enhance learning. These theories describe the basics of human cognitive architecture, in particular the processing limitations of working memory (e.g., Baddeley 1992; Paivio 1986; Sweller 2010), and consider how instructional materials in general should be designed to support learning (e.g., Ainsworth 2006; Mayer 2009; Schnotz 2005). In this chapter, we will discuss these theories and link them to the "choreographies of teaching" approach by Oser and Baeriswyl (2001), who emphasize the need to distinguish between the sight structure of a learning scenario (e.g., instructional materials in a physics lesson) and the underlying deep structure, which refers to the way in which learners process and comprehend information.

By bringing together these approaches, the readers of this chapter will acquire knowledge on how multiple representations can be used in ways that adhere to common instructional design theories on the presentation side and simultaneously supports deep level understanding on the learners' side. First, however, we will clarify what we actually mean when we talk about "multiple representations".

1.2 What Are Multiple Representations?

The term "representation" is used in a very wide fashion in the educational research literature. For instance, one should be aware of whether an external representation (such as a text, a graph, or a picture) or an internal representation (the mental model a learner builds with regard to a certain learning content) is being described.

In an attempt to classify and unitize representations in chemistry, Gilbert and Treagust (2009) distinguish between three types: a phenomenological or macro type (that is, representations of the empirical properties of compounds), a model or submicro type (external representation, e.g., visual models that depict the (assumed) arrangement of entities, such as atom or molecule models, see Fig. 1.1a), and a



(a)

H_2O

H-O-H

(b)

Fig. 1.1 Example for submicro type representation (**a**) and symbolic type representations (**b**) of a water molecule

symbolic type (that is, the submicro type further simplified to symbols, e.g., "Na" or "Cl^-", see Fig. 1.1b).

While Gilbert and Treagust (2009) use the term "representation" for external, visible representations (such as the ones in Fig. 1.1) as well as for internal representations (comparable to mental models), a remarkable amount of instructional design research that deals with multiple representations refers more or less explicitly to external representations, or in other words, any kind of visualizations. For instance, theories such as the Integrated Model of Text and Picture Comprehension (ITPC; Schnotz 2005) or the Cognitive Theory of Multimedia Learning (CTML; Mayer 2005, 2009) focus on a multimedia concept of multiple representations – that is, a combination of textual and pictorial information. With regard to our example of the block and tackle concept, a classical multimedia learning material would for instance include one or more pictures of a block and tackle that are accompanied by explanatory text (Fig. 1.2).

A broader view of external multiple representations is given by Ainsworth (1999, 2006). According to her DeFT (Design, Functions, Tasks) taxonomy, learning with multiple representations means that two or more external representations are used simultaneously. This can include the classical text-picture-combinations that are described in the ITPC and the CTML, but also goes a step further by considering any other kind of combinations of external representations as well. For instance, with regard to our block and tackle example, instead of showing the picture with accompanying text, one might also show the text accompanied by a table that systematically lists examples for weights, number of strands, length of ropes and resulting pulling power.

In this regard, a specific form of representation is characteristic especially for physics education, namely mathematical expressions like, for example, equations or functions (cf. Angell et al. 2008). Generally, mathematical expressions used especially in physics usually describe a system by means of a set of variables and a set of equations that establish relationships between the variables that represent specific properties of the system. For instance, Newton's laws causally describe phenomena of the meso-world. However, looking at micro and macro conditions, quantum mechanics and relativity theory must be used. Another feature of physical modeling is the use of idealized models to reduce influencing variables such as massless or point objects or gas with idealized behavior. The description of such phenomena includes mathematical models, mostly functional relations, such as the above-mentioned Newton's gravity law, Maxwell's equations, or the Schrödinger equation. Such models should thus be taken into account in addition to classical formats of multiple representations such as written text or instructional pictures.

"The mechanical advantage of a block and tackle system is equal to the number of supporting ropes or cables. Notice how the pulling force advantage of a pulley varies depending on the number of strands that it has. If it has a single strand, then the pulling force advantage is 1, which is really not an advantage at all. Two strands give a pulling force advantage of 2, three strands give a pulling force advantage of 3, and so forth."

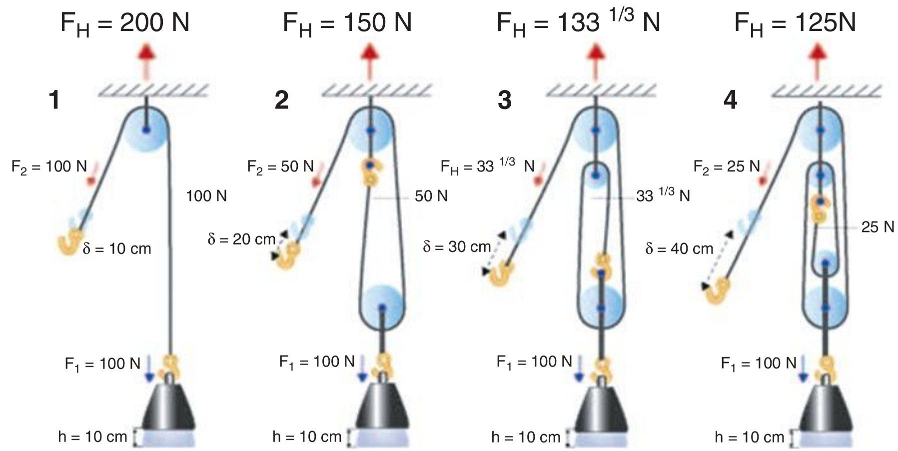


Fig. 1.2. Multimedia learning material consisting of text and accompanying pictures for the concept of block and tackle

In the following paragraphs, we will describe the ITPC, CTML and DeFT model in greater detail, before we will link their views on learning with external multiple representations to the more learner-focused view of internal mental representations by Oser and Baeriswyl (2001).

1.3 Theories on Learning with Multiple Representations

The question of why using multiple representations in instructional materials fosters meaningful learning has been addressed in a remarkable number of studies and led to several well-established theories. Most of these theories are based on assumptions about information processing and the structure of the human mind. More specifically, working memory is assumed to be limited with regard to the amount of information it can process at a certain time (Baddeley 1992). This information can consist of multiple forms of representations, which are either processed in a verbal/auditory or a visual/pictorial channel (cf., dual channel assumption; Paivio 1986), depending on the modality of the information. Similar to the overall capacity of working memory, both channels are assumed to be limited regarding the amount of information they can process at a time and in parallel. In this regard, it is recommended to make optimal use of both channels instead of overloading only one of them. One way of doing so is to stress both channels by using multiple representations in instructional materials.

1.3.1 The Cognitive Theory of Multimedia Learning (CTML)

Based on this view of information processing, the CTML (Mayer 2005, 2009) proposes to use multimedia instructional materials to support deep level understanding and thus meaningful learning. As has been mentioned above, the CTML mainly focuses on multiple representations in the sense of text and picture combinations. In this regard, Mayer (2009) states in his multimedia principle that “Students learn better from words and pictures than from words alone” (p. 223). This principle is based on the assumption that words and pictures are qualitatively different with regard to the information they contain; and because of the different channels in which they are processed, different information contents are being learned and (when learning takes places optimally) integrated to one coherent mental model. It seems that scientists intuitively apply this idea of picture-supported explanations for more than 4000 years; for example when looking at the more than 4500 years old Egyptian stone carving showing Nut, the queen of the sky, spanning the dome of the sky (Metropolitan Museum, New York) or drawings of Galilei (Galilei 1610), who illustrated vall Geller eys and hills on the moon accompanied by verbal descriptions. The multimedia principle has been proven in several studies using paper-based as well as computer-based instructional materials (e.g., Mayer and Sims 1994; Plass and Jones 2005; Schwamborn et al. 2011; for an overview see Mayer 2009, 2014).

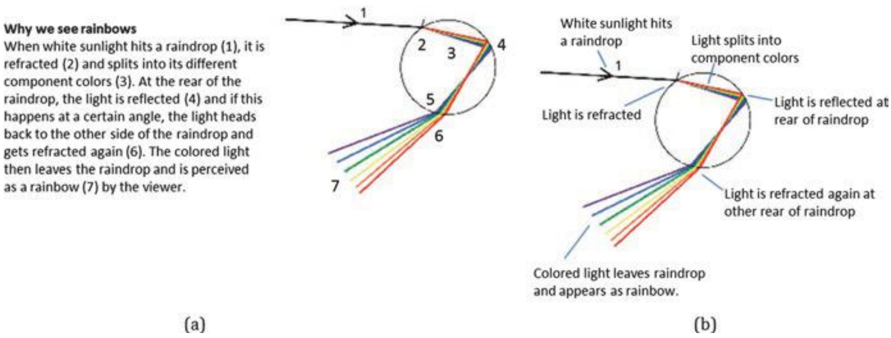


Fig. 1.3 Examples for learning materials that are spatially separated and might cause split attention (**a**) or that adhere to the spatial contiguity principle (**b**)

However, just combining words, pictures, mathematical expressions or other kinds of visualizations does not automatically guarantee meaningful learning. The CTML states several further principles that go into more detail with regard to how multimedia materials should be presented and combined. For instance, the modality principle states that when using text and pictures together, the text should be spoken rather than written, because in this case both the auditory and the visual channel are used instead of overloading the visual channel only. While this principle could be supported in a large number of studies (cf., Ginns 2005; Harskamp et al. 2007), others argue that written text can be as effective given that there is enough time to process both the text and the pictures (e.g., Kalyuga 2005; Tabbers et al. 2004). In this case, written text might even be superior to spoken text, because while the latter is transient in nature, written text can be re-read and scanned for relevant information selectively.

Two less controversial principles that could be shown for auditory as well as for visual multiple representations are the spatial contiguity principle and the temporal contiguity principle. These principles state that when using multimedia learning materials, the different representations (e.g., the text and pictures as shown in Fig. 1.3) should be presented closely together (Ginns 2006; Mayer and Fiorella 2014; Mayer and Moreno 1998). That is, in textbooks, paragraphs explaining a certain phenomenon should be placed right beside the respective picture. Optimally, text parts might even be integrated into the respective parts of the picture. For instance, when explaining the refraction of light in raindrops when teaching about the emergence of rainbows, learning materials as shown in Fig. 1.3a might be less helpful than the more spatially contiguous presentation in Fig. 1.3b, because in the first case, associated parts of the learning materials are presented far from each other. In this case, split attention effects can occur, that is, working memory capacities are stressed with visual search processes that are actually unnecessary and do not contribute to comprehension and learning (Ayres and Sweller 2005; Kalyuga et al. 1999). The same assumption applies to instructional materials that are presented in temporal contiguity – very simply stated, when explaining the concept of block and tackle, the teacher should not talk first and then show the respective picture, but show the picture at the same time as describing the principles depicted there.

The redundancy principle states that when presenting text and pictures together, using identical written and spoken text at the same time is unnecessary and can even hinder learning, because in this case, the same kind and amount of information is presented and has to be processed twice at a time (Craig et al. 2002; Mayer 2009; Sweller 2005). This double attention to text and pictures stresses the respective working memory channels, but no additional knowledge gains can be expected. However, it should be noted that avoiding redundancy does not mean that the multiple representations used in instructional materials are completely different from each other with regard to the information they contain. In contrast, a certain amount of overlap is necessary so that the relations between the representations (that should all aim at conveying knowledge on one certain topic, model etc.) become clear and support the integration of information and thus the construction of one coherent mental model (Scheiter et al. 2008).

The signaling principle (Mayer 2005, p. 183) states that "people learn better when cues that highlight the organization of the essential material are added" (cf., Mayer and Fiorella 2014; Van Gog 2014). That is, when using multiple representations such as text plus picture or a table with an accompanying graph, highlighting techniques such as color coding or printing parts of the text in bold or cursively, can off-load working memory and thus free capacities that can be used for meaningful learning. In this case, learners would not have to use these capacities to search for the most relevant information in instructional materials (Harp and Mayer 1998; Mautone and Mayer 2001).

Finally, the coherence principle states that despite the benefits of multimedia learning and multiple representations, all materials that do not directly contribute to the comprehension of the content to be learned and are thus extraneous materials should be excluded (Mayer and Fiorella 2014). For instance, according to Mayer (2009), text parts and pictures that are interesting, but irrelevant for the actual information processing process should be removed from learning materials, because in this case, working memory capacities are used for paying attention to these unnecessary details, while at the same time, they cannot be used for the construction of schemas, integration of information sources or meaningful learning. Such "seductive details" can even be detrimental for learning when learners are tempted to focus their attention around the wrong kind of information. However, the coherence principle has also led to some controversies in educational research, as it tends to ignore affective variables such as motivation and interest. In this regard, recent research (e.g., Lenzner et al. 2013; Park et al. 2015) has shown that seductive details such as decorative pictures are not necessarily harmful and can even foster learning, when they are able to induce and thus have an indirect positive impact on learning.

Taken together, according to the CTML, multimedia learning materials and thus the use of multiple representations are recommended because, compared to learning with single representations such as text only, they address different processing channels in working memory, contain information of different kinds and different qualities and support the construction of coherent and integrated mental models. In other words, using multiple representations can foster learning.

1.3.2 The Integrated Model of Text and Picture Comprehension (ITPC)

Very similar to the CTML, the ITPC (Schnotz 2005, 2014; Ullrich et al. 2012) also assumes that the processing of multiple representations takes places in two different channels, which are called the auditive and the visual channel. In a first step, all incoming information is processed on a perceptual level (e.g., text-surface representations or visual images). This perceptual level is followed by a cognitive level when information is being processed in working memory in a verbal and/or pictorial channel. Contrary to the CTML, which states that visual and verbal information first lead to the construction of visual and verbal mental models, which are later on integrated into one coherent mental model, the ITPC assumes that this integration and building of one mental model takes place right from the beginning of the processing of multiple representations. That is, information being processed in each of the two channels is aligned and matched from the start of information processing.

In the ITPC, the benefits of learning with multiple representations (in this case, again, primarily with text-picture combinations) are based on this assumption of an integrative processing of verbal and pictorial sources of information; however, an important condition for these benefits to take place is that the respective "verbal and pictorial information are simultaneously available in working memory" (Horz and Schnotz 2008; p. 50). Only in this case, learners are able to recognize that the different representations belong together and can map them to their respective counterparts to make use of the information contained in both of the sources.

In line with the CTML and the ITPC, the work of Ainsworth (2006, 2014) proposes that learning with multiple representations is not automatically effective, but that these representations should fulfil certain functions. In contrast to the CTML and the ITPC, however, Ainsworth's view of multiple representations comprises much more than only text-picture combinations. Her framework will be described in greater detail in the following.

1.3.3 The DeFT (Design, Functions, Tasks) Framework for Learning with Multiple External Representations

According to Ainsworth (2014; see also Tsui and Treagust 2013), learning with multiple representations takes places when any two or more external representations are used in instructional materials. In a classical multimedia view, this can comprise (written or spoken) text and accompanying pictures, but multiple external representations (MERs) can also include photos, diagrams, tables, graphs, concept maps, or even notes taken during learning. In this regard, specific combinations of MERs are not effective in themselves, but they should fulfil certain functions for learning (see Fig. 1.4).

First, learners can benefit from MERs if the different representations fulfil complementary functions, that is, each of the single representations should at least partly

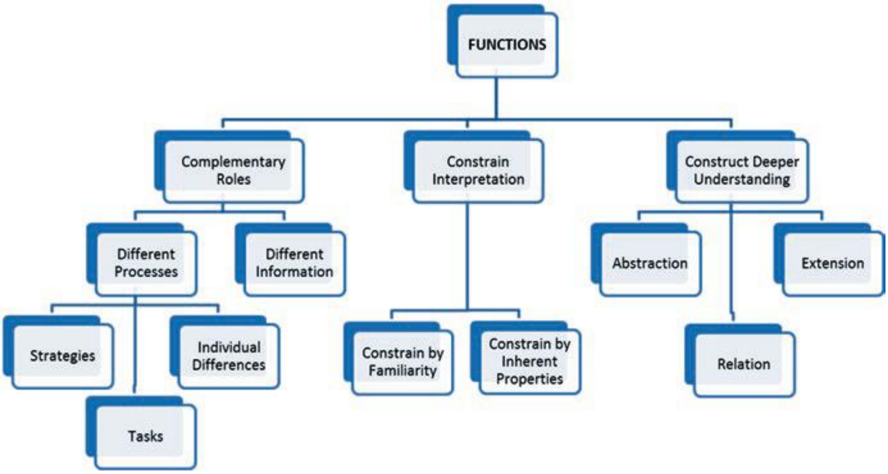


Fig. 1.4 Functions of multiple external representations according to the DeFT framework (Figure adapted from Ainsworth 2006)

Time in seconds	Velocity Car 1	Velocity Car 2
0	0	0
1	4	1
2	8	4
3	12	5
4	16	7

$$a(t) = \frac{\Delta v}{\Delta t}$$

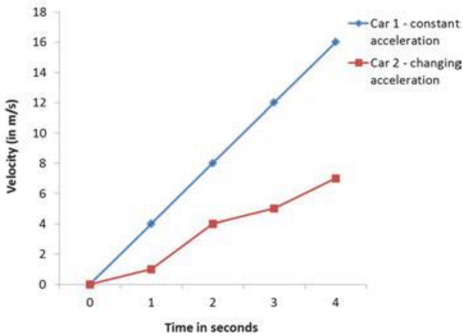


Fig. 1.5 Example for learning materials on acceleration using multiple external representations

offer unique information or support different inferences (Ainsworth 2014). In other words, multiple representations support comprehension, when they either contain qualitatively different aspects of the information to be learned, or when they convey the same information, but in different ways. For instance, when the concept of acceleration is taught for rectilinear motion, the teacher could just state or write that constant acceleration can be expressed as the differential quotient of (change in) velocity divided by the time interval, Δt, and could show this quotient along with the formula for acceleration. In addition, the teacher could present a table with exemplary values for the acceleration of a vehicle and depict these values by means of the respective graph (see Fig. 1.5).

In Fig. 1.5, the table and the graph actually contain partly the same but, due to different types of representation, also complementary information, in addition generalized by the function a(t). In this case, using multiple representations (that is, presenting all three to the learners) would support the steps of a learning process from changing velocity in time and for rectilinear motion to the notion of acceleration as a general description of a phenomenon.

Another advantage of MERs is that they can support different cognitive processes, because individual differences can be taken into account. That is, learners could "choose to work with the representation that best suits their needs" (Ainsworth 2006, p. 188). Similarly, MERs can foster learning, when learners can choose the representation that best fits the requirements of a certain task – that is, performance is enhanced when the structure of the external representation is similar to the structure of information required to solve the respective problem (cf., Gilmore and Green 1984). Finally, with regard to different processes, presenting learners with MERs might encourage them to use more than one strategy to solve a problem (Ainsworth and Loizou 2003; Won et al. 2014). For instance, Tabachnek, Koedinger and Nathan (Tabachneck et al. 1994) found that using multiple strategies when being exposed to multiple representations was twice as effective as just using one of the strategies in isolation.

In addition to fulfilling complementary functions by supporting different cognitive processes, MERs can also provide complementary information, that is, the single representations contain (partly) different but complementary aspects of the information. It would be harder or even impossible to learn with one single representation in isolation, for instance, learning about how a block and tackle works would probably be possible with just a written text describing the mechanisms behind and the relations between the number of ropes, position of roles and pulling force. It would, however, be much easier (and learning might take place much quicker) with an accompanying picture (cf., Fig. 1.2), because this picture contains visual / spatial information that can be seen at once, which is not possible to realize in a sequentially organized text. The picture in this case would complement the text by providing additional information.

Besides taking into account that different representations contain complementary information, MERs can also support learning if they constrain each other's interpretation possibilities when being presented together. As can be seen in Fig. 1.4, this can be done in two ways. First, if one representation is significantly more familiar to the learner than the other, this familiar representation can constrain the interpretation of the other one. According to Ainsworth (2006), this is often the case when complex graphs are used in instructional materials. Interpreting these graphs can be challenging for less experienced learners. Consequently, providing a table or a picture or an explanatory text along with the graph would help learners make sense of the data depicted in the graph and thus foster learning. Second, besides familiarity, also inherent properties of the representations can constrain each other's interpretation. For instance, imagine working in a high-class restaurant and having to learn how the cutlery has to be positioned around the plates. Just being told "Put the desert spoon and the cheese fork above the plate; thereby the spoon should be above the fork." might give you some information, but not enough with regard to the directions in which the spoon and fork should point or the distances between plate, fork and spoon. Showing a picture at the same time that depicts a standard cutlery arrangement would immediately constrain the interpretation options for the above instruction. Similarly, the interpretation of descriptive representations can be constrained by presenting them along with a depictive representation (Schnotz 2014) – for example, the word "force" might lead to very different internal images unless it is accompanied by a picture, such as a pulley with indicated absolute values of pulling and lifting forces and their directions (cf. Fig. 1.2). (For a more fine-grained explanation of descriptive versus depictive representations, see the following sections.)

Finally, the third function of multiple external representations according to the DeFT framework is that such combinations are able to promote a deeper level of understanding. This is the case when learners are able to integrate information from the different representation modes and thus gain knowledge that would be hard to infer from just one representation alone (Ainsworth 2006). In order for MERs to construct such a deep conceptual understanding, three processes need to be considered. First, learners should be able to abstract relevant information from the representations and by doing so, construct references across the multiple representations that represent the underlying structure of a content to be learned. Second, learners should be able to extend the knowledge they have with regard to one representation to learning with other representations without fundamentally reorganizing the actual knowledge. For instance, when having learned about Ohm's Law by means of the formula $I = V/R$ (with R = constant and independent of current and voltage) and a graph depicting the electric current as a function of the ratio between voltage and resistance, learners should be able to generalize this knowledge to the comprehension of respective tables or to a related solution of the equation. Third, learners should be able to relate representations to each other, that is, they should be able to translate between representations – for instance by being able to draw a graph when the acceleration formula is given along with the table with exemplary values. According to Ainsworth (2006), "this goal of teaching relations between representations can sometimes be an end in itself" (p. 189).

To sum up, multiple external representations according to Ainsworth (2006, 2014) can support learning when they are designed in a way that they (a) support different cognitive processes or include complementary information, (b) constrain interpretation options, thereby preventing inaccurate interpretations and (c) promote deep level understanding by means of abstraction, extension and relation (cf., Tsui and Treagust 2013). Especially with regard to the third proposed function of MERs, an overlap with the Cognitive Theory of Multimedia Learning and the Integrated Model of Text and Picture Comprehension can be seen in that in all three theories, multiple representations, especially multimedia learning materials, are assumed to be beneficial for learning only if learners are able to recognize that the different representations are meant to convey the same knowledge, and if the learners are able to mentally relate the different sources of information to each other and integrate them with existing knowledge and schemas already stored in long-term memory. However, these benefits of multiple representations depend on the kind of external representation (text and/or pictorial representations) used as well as on individual learner characteristics. These aspects are the focus of the next two sections.

1.3.4 Types of External Representations and Their Benefits for Learning

In the previous section, we have described the coherence principle of the CTML (Mayer 2009; Mayer and Fiorella 2014), which states that interesting but irrelevant materials should be excluded from learning contents. This already points to one important characteristic of external representations, namely the question, whether they have any instructional value. Although there are newer strains of research that also support the assumption that seductive details such as decorative pictures can be (indirectly) beneficial for learning (Höffler et al. 2013; Opfermann et al. 2014) because of their motivational potential, we will focus on external representations that are, at least to some degree, instructional, namely, they have some kind of explanatory value. Such representations can be divided into verbal representations such as written or spoken text and pictorial representations such as pictures, graphs, photos or drawings.

1.3.5 Characteristics of Text That Are Beneficial for Learning

When one or more of the multiple external representations used for learning contains text, the obviously most important aspect in this regard is that the text is comprehensible (cf., Leutner et al. 2014). To ensure text comprehensibility, Langer, Schulz von Thun and Tausch (Langer et al. 2006) introduced the "Hamburg Approach" for language comprehension, which proposes four characteristics that written or spoken text should fulfill to foster learning. The first characteristic is simplicity, that is, sentences should be formulated concisely, and complicated words and phrases should be avoided whenever possible. Second, with regard to organization, text should be clearly arranged, and an internal as well as external structure should be visible. Third, conciseness is important in that sentences should be short and not long-winded. Fourth, text should be able to support some kind of motivational-affective stimulation, that is, it should be able to arouse the interest of learners. Overall, it is recommended that the longer a text is and the more complex the topic to be learned, the better it is not to present the respective text as a whole, but to split it up in smaller and meaningful units that can be processed consecutively – a suggestion that is also reflected in the segmenting principle of the CTML (Mayer and Pilegard 2014) or in suggestions on how to offload working memory by optimizing instructional design (cf., Cognitive Load Theory; Sweller et al. 2011).

1.3.6 Characteristics of Pictorial Representations That Are Beneficial for Learning

In general, pictorial forms of multiple representations can be found in several facets. For instance, a distinction can be made between static (e.g., pictures, photographs or drawings) and dynamic visualizations (e.g., videos, animations or interactive graphs). In their meta-analysis, Höffler and Leutner (2007) found in this regard that animations are on average superior to static pictures (with a small to medium effect size of d = .37), but that this superiority mainly shows up when the visualizations are very realistic (that is, real videos) or when dynamic contents have to be learned, such as steps of a certain process. For instance, for a learner to understand how a block and tackle really works, an animation might be preferable, while a static picture such as the one in Fig. 1.3 would do if the goal was to learn about the relation between ropes, roles and pulling power (see also Höffler et al. 2013).

Another distinction that has attracted a considerable amount of recent research refers to the question, whether a visualization such as a picture is presented to the learners along with the other representations such as the text, or whether learners are requested to generate external representations by themselves. In this regard, the generative drawing principle (Schwamborn et al. 2010; Schmeck et al. 2014; for an overview see Leutner and Schmeck 2014) states that asking learners to draw pictures of the instructional contents themselves while reading a text can enhance learning because it encourages learners to engage in deeper cognitive and metacognitive information processing and thus fosters generative processing. The finding that self-generated drawings can improve learning has been confirmed in several studies (e.g., Ainsworth et al. 2011; Van Meter and Garner 2005), but these benefits are also subject to several preconditions such as the quality of the drawing or the question whether instructional support for instance by means of drawing tools is available (cf., Leutner and Schmeck 2014).

Irrespectively of whether a visualization is static or dynamic and whether it is presented or self-generated, a further distinction can be made following an approach by Schnotz (2005), who distinguishes between descriptive (or propositional) and depictive representations. Descriptive representations do not have any structural similarity with the content matter they are supposed to describe and are often used synonymously with symbols (see Fig. 1.6a). For instance, the letter "I" or the word "electric current" do not look like electricity, they are just meant to describe the concept. Similarly, "--⊗--"does not look like a light bulb, but once a learner is used to this symbol in technical and physics domains, he or she is able to learn and work with it. Depictive representations, on the other hand, can be compared more to icons that show similarities or structural commonalities with the respective referent they are supposed to depict. For instance, the drawing of a car is depictive – although not being identical with a real car, it shows enough overlap to be recognized as a car (see Fig. 1.6b).

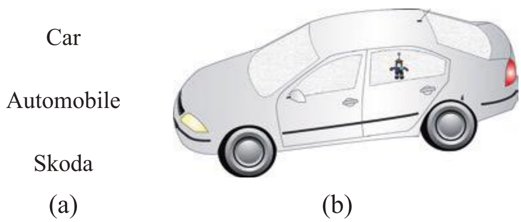


Fig. 1.6 Examples for descriptive (**a**) and depictive (**b**) representations of a car according to Schnotz (2005)

While descriptive representations appear to be more suitable to convey abstract knowledge, depictive representations are informationally more complete (e.g., the drawing or photograph of a car contains more details at one sight than the word "car" or even the more concrete word "Skoda Octavia GreenLine silver". Concrete knowledge and the drawing of inferences can thus be better supported by providing depictive representations. It has to be noted, however, that this advantage of being informationally more complete can also cause opposite effects when there are too many details that are not needed for learning and that distract learners and stress cognitive capacities that could otherwise be used for meaningful learning (cf., extraneous cognitive load; Sweller et al. 1998).

Furthermore, pictorial representations can be classified according to an approach by Niegemann et al. (2008). The authors distinguish between realistic pictures (e.g., the drawing or photograph of a block and tackle such as in Fig. 1.3), analogy pictures (e.g., depicting the limited capacity of working memory by means of a bottle that can only be filled to a certain extent until it overflows), and logical pictures (such as diagrams and graphs, see Fig. 1.5). With regard to realistic pictures, research has shown that the degree of realism that is beneficial for learning depends upon several factors such as the prior knowledge of learners (Klauer and Leutner 2012). For instance, a highly realistic picture might overburden learners because – as mentioned in the previous paragraph – there is extraneous load created through the attempt to process all the details that are actually not necessary for comprehension (see also Dwyer 1978; Rieber 2000). According to Niegemann et al. (2008), a medium level of realism should be beneficial for learning in most cases.

Analogy pictures (in terms of the assumptions by Schnotz 2005, these would be descriptive rather than depictive visualizations) do not necessarily show structural similarities with the contents or object that they are supposed to depict on a visual or surface level; however they relate to each other in some kind of analogy relationship (Leutner et al. 2014; Niegemann et al. 2008). Such representations are especially suitable when abstract concepts have to be illustrated – for instance, "electrical energy" is an abstract term and rather a mental model in itself, but it can partly be visualized by using water circuits as done by Paatz, Ryder, Schwedes and Scott (Paatz et al. 2004). Furthermore, analogy pictures support transfer abilities, given that learners understand that they are learning with analogies (cf. DiSessa et al. 1991; Glynn 1991; Leutner et al. 2014).

Finally, logical pictures also do not have structural or obvious similarities with the contents they represent, but they depict these contents schematically. For instance, the graph in Fig. 1.5 is a schematic comparison of two cars with different amounts of acceleration. In this regard, all kinds of diagrams can be classified as logical pictures. According to Niegemann et al. (2008; see also Leutner et al. 2014; Schnotz 2002), diagrams such as pie charts, bar charts or line charts are more effective for learning than other forms of diagrams, because they are more familiar to learners. Furthermore, pie charts are especially suitable to convey information about the composition of a certain content to be learned and should be used when the learning content as a whole is of particular interest – for instance, when the distribution of the capacity of power generation for different sources in a country is demonstrated. When, on the other hand, quantitative differences between elements or information units need to be depicted, bar charts should be used (e.g., to show the development of alternative power generation over time).

Overall, when using logical pictures in multiple representations, one should make sure that learners are familiar with the conventions of how to process and interpret such representations (cf., Schnotz 2002; Weidenmann 1993). For instance, bar charts should show the bars in a bottom-up design and not from left to right.

To sum up, multiple external representations can be presented to learners in many different forms with each being more or less suitable to convey certain kinds or aspects of knowledge. In physics learning, all of such aspects (e.g., the retention of facts, the comprehension of mechanisms, the application and generalization of functional relations) have to be considered when an overall and complete range of conceptual and procedural knowledge and transfer are to be acquired. Besides the inherent characteristics of each representation, a second important factor that needs to be considered are individual learner characteristics, which can serve as moderators between instructional design and learning outcomes. These characteristics will be focused on in the next section.

1.4 The Role of Individual Learner Characteristics for Learning with Multiple Representations

The characteristics and individual prerequisites that learners bring into a certain learning scenario have been subject to a large amount of empirical studies, not only in physics and science teaching (e.g., Aufschnaiter et al. 1970; Duit 2008; Incantalupo et al. 2014), but also for learning with multiple representations in general. For instance, Mayer (2009) in his individual differences principle of the CTML states that multimedia design effects that are beneficial for low prior knowledge learners do not necessarily need to be as effective for high prior knowledge learners and can even be detrimental for them, for instance because of redundancy effects (Kalyuga and Sweller 2014). In line with this, Kalyuga (2005) assumes an expertise reversal effect for instructional materials in that experts in a certain domain get along much better with reduced multimedia materials and less guidance. For instance, university students at later stages of their studies who are learning about the relativity theory might need remarkably less information than high school students who are just introduced to the theory.

A second learner prerequisite that appears to be especially important when it comes to learning with multiple representations that contain any kind of visual information is the spatial ability of a learner. For instance, according to Mayer and Moreno (1998), students with high spatial ability can better retain multiple visual representations in their working memory, relate such visual/spatial elements to each other and thus better learn when words are presented together with pictures. Spatial ability has been investigated especially with regard to dynamic representations (e.g., animations or videos), where Höffler (2010; Höffler and Leutner 2011) found evidence for the so-called ability-as-compensator hypothesis. In other words, learners with low spatial ability might benefit more from dynamic visualizations because these provide an external representation of a process or procedure that helps learners to build an adequate mental model of the information to be learned, whereas constructing such a mental model by using static pictures should be much more difficult for low spatial ability learners (Hays 1996).

Considering spatial ability as an important moderator between different multiple representations and learning success might be especially important in a domain that is as abstract as physics. On the one hand, much of the information found in instructional materials is pictorial (and thus very concrete); on the other hand different MERs require the construction of integrated mental models. We thus recommend taking spatial ability into account whenever research on physics learning includes (at least partly) visual multiple representations.

In addition to prior knowledge and spatial ability, several other learning characteristics have been focused on in recent research, including the cognitive style of learners, their epistemological beliefs, metacognitive and self-regulatory abilities and motivational as well as other affective variables. While these variables do not explicitly relate to learning with multiple representations, such variables can have an impact on how learners approach a learning situation, how they structure and regulate their learning process, or how much attention and perseverance they show during learning (cf., Duit 1991; Höffler et al. 2013).

Taken together, individual learner characteristics should be taken into account when designing instructional materials that contain multiple representations, as such characteristics can serve both as moderators (Schraw et al. 1995) or mediators (Davis et al. 1989; Opfermann 2008) between instructional design, strategies and activities deployed during learning as well as cognitive load and learning outcomes. Such characteristics determine how multiple representations are processed individually and whether learners are able to translate the external representation into an internal and coherent mental model (see also Gerjets and Hesse 2004). This view is closely related to the choreographies of teaching view introduced by Oser and Baeriswyl (2001). This approach is shortly described in the last section of this chapter.

1.5 The Theory of Choreographies of Teaching

In the previous sections, we have described how multiple representations can be classified, which characteristics they should have and how they should be combined to support meaningful learning. In this discussion, we contextualize these representations by providing examples in physics and describe how individual learner characteristics relate to learning with multiple representations. In short, a certain instructional design that is effective for one learner might not be helpful for another and vice versa.

As a consequence, knowing as many external representations of a concept as possible and the logical connections between them is one of the necessary prerequisites to gain knowledge at university as well as at school and should therefore also be an important part of physics teachers' professional knowledge. This is in line with the "choreographies of teaching" introduced by Oser and Baeriswyl (2001; see also Geller et al. 2014; Ohle 2010). Their approach to learning emphasizes the need to design teaching explicitly according to learning goals. That is, not only the sight structure (everything that is visible, such as instructional materials including multiple external representations) of a lesson is important, but it has to be taken care of the deep structure, which comprises so called basis models and underlying processes of learning that should be supported. Teachers can introduce the deep structure of the discipline by providing learners with different instructional designs to choose from, which is also called offers or opportunities to learn in this approach. Similarly, Reyer (2004) distinguishes between the surface structure of a lesson and their deep structure, which includes learning processes, goals and strategies that can be applied by learners when a certain surface structure is provided.

For example, to understand the effect of gravity, learners need to develop a prototype in a first step. This might be supported by teachers showing the legendary apple of Newton paradigm in a demonstration – this would be a part of the sight or surface structure of the lesson. To build up a coherent mental model (as part of the deep structure), learners then need to interpret this visual external representation and to transfer the information into an internal text-based representation – an approach that is very similar to the ITPC approach by Schnotz (2005) and its description of building (text-based) propositional mental representations and (visual) mental models and integrating them into one coherent schema of the learning content.

To organize their offers to learn and to support the students' construction of mental models, teachers should know several of such prototypes for the same concept. In a next step, the text-based prototype must be described in detail by analyzing its essential categories and principles, which includes the reconstruction of measurements and of mathematical modelling of underlying concepts. Third, to deal actively with the concept requires mental activities like the application of mathematical formalisms or of Newton's law of gravity or Newton's second law of motion, for instance by students conducting their own experiments. In this regard, a physics law is differently represented. In the first case it is used as the description of a phenomenon, and in the second case, it must be interpreted as a source to design an experiment. As a last step, learners should be able to apply the developed concept in different situations, like for example to describe the sun-earth-moon system or the gravity conditions in the International Space Station (ISS).

Following the model of Oser and Baeriswyl (2001), multiple external representations as part of the sight structure of a lesson should be used as a means to support processes related to the deep structure of the lesson.

1.6 Summary

In this introductory chapter, we have presented theories and approaches on learning with multiple external representations (MERs). We have argued that, based on well-established views on information processing and working memory, multiple external representations are suitable to foster learning, because in contrast to learning with single representations, MERs address different sensory and working memory channels instead of overloading only one channel. By using MERs, several functions that are beneficial for learning can be fulfilled – more specifically, they can support learning and deep level comprehension if they provide complementary information or address different cognitive processes and/or if they constrain each other's interpretation. We also emphasized that such beneficial effects do not only depend on the kind of representation combination (e.g. their spatial and temporal contiguity), but also on the inherent characteristics of the representations as well as on individual learner characteristics. Finally, the instructional design side and thus the sight structure of learning scenarios (e.g., MERs, their combination and characteristics) should be distinguished from the underlying deep structure, and multiple external representations as part of instructional materials should be designed according to this deep structure, for instance by offering learners different opportunities to learn using respectively related representations. This demand can be met by multiple external representations in a much better way than by single representations, because the inherent nature of MERs enables learners to choose between different representations and learn with the one that best fits their learning preferences, individual prerequisites or requirements and characteristics of the learning task.

To sum up, and as described above, using multiple external representations is a tool for facilitating the understanding of concepts for learners and for supporting them in task solving. In addition, using MERs is a necessary prerequisite for students' own construction and reconstruction of meaning not only from instructional materials provided but also to understand the internal structure of physics concepts expressed in different forms of representations. In turn, a broad knowledge of adequate external representations that can be used as such instructional materials is a necessary constituent of teachers' professional knowledge not only in physics education, but in general.

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Part I
Multiple Representations: Focus On Models and Analogies

Reinders Duit

Models have played a significant role in the history of science, i.e. the stepwise development of science over long periods of time as well as in teaching and learning science in schools and elsewhere. The literature on models and modelling is abundant. It is hardly possible to overestimate their role in science as well as in teaching and learning science. Models and analogies are closely linked – as analogies are the means that are at the heart of the meaning of a particular model. Accordingly, analogies play a significant role in various chapters of the present volume. The link between models and representations is nicely summarized by Angell and Kind in the introduction of Chap. 2 by stating: "Modelling and representations were placed together because representations are tools for modelling; they are what models are made of."

The chapter by Angell and Kind is based on a nation-wide project in Norway to develop a physics course for upper secondary students focussing on the role of conceptual and mathematical modelling in guiding upper secondary students to understand physics. The rationale for the study draws on a social cultural perspective – which is also the case for other studies discussed in the present volume on multiple representations in physics education. In addition the epistemological framework draws on design based research. It is worth pointing out that the study presented includes a substantial number of new ideas for teaching and learning physics in schools and at tertiary level. To just mention one example, there is an activity of investigating the relation between force applied and elongation of certain bodies. But instead of using the traditional linear springs they use "jelly babies"- sweets that show linearity in a certain range of elongations but non-linear ones if the forces are becoming too large. The evaluation of the course includes qualitative and quantitative data – which is in line with the design based research approach adopted. The quantitative data include comparisons of learning outputs with a control group taught "traditionally".

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Interestingly, the control group outperforms the group taught the new way. Reasons presented for this surprising results seem to be convincing.

Whereas in the previous chapter Angell and Kind investigate the outcomes of an innovative course drawing on familiar and well established kinds of representations Gravel and Wilkerson in Chap. 3 focus on representations so far given not much attention in science education research – computational artifacts – i.e., approaches drawing on computer simulations. Interestingly also here a cultural perspective is adopted. The authors put what they intend in the following way: "How does a learning community integrate a particular computational artefact into a shared multi-dimensional toolkit they use for communicating and reasoning about scientific phenomena." They argue that such artefacts are becoming more and more important the past years. They illustrate their points by documenting the sense making processes of a group of physicists and mathematicians to explore the behaviour of liquid crystals and of a group of fifths grade students using a student generated computer simulation to reason about the processes of evaporation and condensation. Similarities and differences of the discourses in the groups are discussed.

Finally, Lin and Chiu in Chap. 4 link research on multiple analogies and multiple representations. They investigate a classical domain of student pre-instructional conceptions research, namely on the various students' ideas of simple and more complex electric circuits. The authors show that linking the two perspectives allows to interpret findings from a new more inclusive and hence more powerful perspective. The research found that unless the analogical material was well designed, alternative conceptions may be formed and the cognitive load increased. Hence, the study significantly contributes to understanding the particular power of both perspectives – namely multiple representations and multiple analogies.

Chapter 2
Teaching and Learning Representations in Upper Secondary Physics

Per Morten Kind, Carl Angell, and Øystein Guttersrud

2.1 Introduction

Physics requires students to use and move between many forms of representations (Angell et al. 2004; Dolin 2002; Erickson 2006; Hubber et al. 2010). They may, for example, observe free fall movement in real-life experiments, describe this movement using a conceptual diagram or a computer simulation, use a mathematical equation to calculate position and speed of the falling object, and describe changes to these variables in a table or graph. Students often find these uses of representations, and the translation of information between them difficult. Researchers, therefore, have suggested to explicitly stress the use of different representations when teaching physics (Danish and Enyedy 2007; Eilam and Poyas 2008; Tang et al. 2014). This chapter presents a project – PHYS21 – that placed teaching of representations together with conceptual and mathematical modelling in a physics course for upper secondary students in Norway.

The aim of the project was to develop teaching material and strategies to teaching physics, and to investigate effects of these in a natural classroom setting. Modelling and representations were placed together because representations are tools for modelling; they are what models are made of. Understanding representations and how these can be manipulated is therefore believed to be a prerequisite for developing modelling skills. Physics, in particular, makes use of mathematical representations and uses mathematics to describe phenomena, construct models and solve problems. Physics students, however, do not always see physics formula and

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equations as modelling tools (Angell et al. 2004). Students typically see physics and mathematics as separate modes of thinking, which means they have problems interpreting the physical meaning of a mathematical equation and do not see the physics argument when a formula is manipulated mathematically. PHYS21 aimed at improving this by explicitly introducing representations and modelling in the physics curriculum. The project had three main research questions. The first question (RQ1) regarded the extent to which we could change Physics towards a more explicit teaching of representations and modelling by developing new teaching material. We wanted, however, teachers not to use the material blindly but to gain understanding about physics models and representations and to commit to such understanding as an aim for physics teaching. A second research question (RQ2), therefore, asked what changes happened to teachers' conceptions of the physics curriculum and teaching when introduced to the material. The third question (RQ3) asked if the intervention material improved students' understanding of representations and their ability to use representations in modelling and problem solving.

The chapter starts by outlining a theoretical rationale accounting for the roles of representations in physics and in physics learning. This rationale takes a socio-cultural perspective and describing representations as cultural artefacts developed in the science culture to communicate scientific ideas and support scientific reasoning. In this view, scientists make use of representations as cognitive tools (Netz 1999). Modelling, similarly, is described as a cultural style of reasoning (Crombie 1994; Hacking 2012) that draws on particular types of representations. Learning to reason scientifically, therefore, depends on being able to interpret and apply these representations. From this rationale we combine modelling with other styles of reasoning to explain the concept of empirical-mathematical modelling, which we introduced in the project PHYS 21 to communicate the rationale to teachers and students. Next, we present teaching material from PHYS 21 operationalising this concept and the methodology used to answer the research questions. Findings in the project are presented in separate parts to describe effects on teaching (RQ1), teachers' conceptions (RQ2) and students' learning (RQ3). Somewhat surprisingly the project did not make students in an experimental group score higher on an achievement test than students in a control group. Reasons for this and reflections of what can be learned from the project are key issues in the last section of the paper. The project has been presented in other publications (Angell et al. 2007, 2008; Guttersrud 2008), but these describe parts of the project only. The current chapter will portray an overview of the project and reflect on its implications for further research and practice. The project covered a full physics syllabus, but the chapter will use examples from force and motion only.

2.2 Theoretical Rationale

Rationales explaining representations in teaching and learning are commonly based on a cognitive-psychological perspective and look towards the advantages of activating different sensory (auditory and visual) channels. Sweller et al. (1998)

cognitive load theory and Mayer's (2003) dual sensory processing theory, for example, both relate the sensory channels to the limited capacity of the working memory. Information from the sensory channels, they suggest, is not stored in the mind passively but rather interpreted into mental constructs and models by drawing on knowledge from the long term memory. Because of the limited capacity of the memory, providing measured but coherent representations with different modalities can support the learning and help producing intended, logical mental constructs. Although valuable, this rationale in our view is insufficient to explain the particular role of representations within disciplinary domains.

The socio-cultural theories offer a different perspective, firstly, by coalescing knowledge and reasoning. Both are socially constructed, which means the science culture has invented scientific reasoning to answer and solve conceptual problems (Latour 1987). This makes science anti-positivistic, because there is no universal objectivity in science and science does not answer to any universal methods or rules of inference (Latour and Woolgar 1986; Pickering 1995), but more importantly, it makes scientific reasoning knowledge-based. To reason scientifically, in other words, is fundamentally based on using scientific conceptual, procedural and epistemic knowledge.

Secondly, the socio-cultural perspective shifts focus from learning as something that occurs exclusively inside people's heads to something that is played out in communities (Ford and Forman 2006). More specifically, it draws a principal distinction between low level mental functions that are innate, such as perception, and those that relate to cultural learning. Vygotsky (1978) refers to these two levels of cognition as elementary and higher mental functions. Higher mental functions, he claims, have a cultural origin and exist in the cultural practice before they are learned by the individual through use of language and cultural tools. Teaching, accordingly, should use a range of different communicative approaches (Mortimer and Scott 2003), and make use of the domain-specific concepts and tools.

Representations, in this perspective, play a crucial role for expressing and internalising higher mental functions. They are cognitive tools invented by the scientific culture to carry out, and communicate, scientific reasoning. Netz (1999) gives an example by explaining of how the lettered diagram, i.e. geometric figures, became the essential representation of mathematical-deductive reasoning in the Ancient Greece. It was Euclid who followed Aristotle's syllogism and used the diagrams as a way of expressing deductive reasoning. By putting the reasoning on paper he could improve the argument and communicate the reasoning with other philosophers and mathematicians. Gradually, the diagrams became the essence of this type of reasoning, used by other mathematicians and scientists for centuries. Galileo, for example, in his Dialogues concerning two new sciences (Galilei 1991), published originally in 1638, applied Euclid's representation to develop and communicate theorems about motion of objects. Later, of course, Newton and Leibniz invented calculus, which replaced the lettered diagram with mathematical formulas and opened up a range of new ways of doing mathematical-deductive reasoning about force and motions, and today still more types of mathematical representations have been added on. The key points, however, are firstly, that representations are an integral part of reasoning in science. Scientists have invented representations together with the reasoning, and secondly, that anyone learning to reason scientifically has to understand and use these domain-specific representations.

According to Crombie (1994), the science culture has developed six different styles of reasoning, and three of these have a particular emphasis in physics. The first is the mentioned mathematical-deductive reasoning, which started in the Ancient Greece and uses mathematical equations and diagrams as the main representations to carry out deductive reasoning. The second is model-based reasoning, which emerged in the medieval period with an influence from art and religion to go beyond the observable and set out hypothetical explanations. This style of reasoning uses a vast range of tools to represent knowledge and processes, but many representations have become standardised. Students, for example, learn to draw light as rays in optics and forces as arrows in mechanics. The reasoning, of course, also uses mathematical representations, but somewhat differently than in the deductive argument. Mathematical representations are created inductively to develop and express relationships between variables. The third style of reasoning is experiment-based reasoning, which is aimed at gathering data and testing theories. This reasoning emerged later than the two previous, in the sixteenth and seventeenth century, when scientists started treating observations as evidence for universal statements (Hacking 1982). Key representations in the reasoning are ways of reporting and expressing trends in data, but also ways of showing how and why data have relevance for theories. Experiments, for example, are expressed in explanatory diagrams that draw on physics theory, and not just as pictures of laboratory equipment.

The three styles of reasoning are used together in a triad. Scientists, for example, may use model-based reasoning to create a conceptual model of a science phenomenon, expressed in a diagram and/or as a mathematical equation, then use deductive arguments in a conceptual or mathematical form to make predictions, and last test these predictions in experiment-based reasoning (Giere et al. 2006). The reasoning, of course, does not always have this clear direction or structure, and any stage requires scientific argumentation to evaluate premises and to decide an outcome (Toulmin 1958). Adding the three styles of reasoning together, however, suggests physics makes use of empirical-mathematical modelling, which was used as the overall concept to communicate the cultural styles of reasoning, and their aligned representations, to teachers and students in PHYS 21.

Ford and Wargo (2012) argue that understanding a scientific idea includes both conceptual and epistemic aspects. Firstly, students should be able to use the idea to explain a natural phenomenon; next, they should be aware that it might be one among a multiplicity of alternatives; and last, they should be able to explain why the scientific idea is superior to alternatives based upon an evaluation, "which involves relating it to evidence and considering how it furthers our understanding of the natural phenomena it explains" (p. 374). They further suggest all these three aspects of understanding can be brought into teaching by appropriate framing of scaffolding activities, which direct students to carry out and reflect on the intended processes. In the beginning, this scaffolding can be tight and students, and teachers, are guided very directly to a particular line of argument, but later, as students' understanding develops at all three levels, the scaffolding can be loosened and students challenged to demonstrate the similar understanding in a more open dialogical teaching.

2.3 PHYS 21 Teaching Material

PHYS21 applied a parallel rationale to Ford and Wargo (2012) described above. A series of scaffolding activities (see examples below) were developed to operationalise empirical-mathematical modelling in physics teaching by using their aligned representations.

The project made an adaptation of the ordinary national curriculum for upper-secondary physics in Norway by replacing one out of eight stated attainment targets (Thermal Physics) with Modelling. The idea was not to teach empirical-mathematical modelling and representations just as one topic, but as a base throughout the course. Emphasis was put on making the reasoning and the representations explicit to students and helping them developing understanding about physics as a modelling activity. To operationalise this, the teachers were provided with a booklet that presented the underpinning rationale together with activities and suggestions for how to use these in the teaching. A parallel booklet was also made for the students. Some activities in these booklets were made compulsory – or strongly recommended – for the PHYS 21 course and used to introduce representations and empirical-mathematical modelling, but in general it was made clear that each individual teacher should adapt the rationale and the activities to his or her personal preferences for physics teaching.

Two activities, described thoroughly in Angell et al. (2007), will serve as examples of scaffolding activities in the project. In the first activity students were invited to explore an unknown phenomenon: the relation between force and elongation of jelly babies (elastic jelly sweets). They were guided to collect data and to draw graphs and construct and interpret mathematical expressions to describe the phenomenon. This experiment usually produces data (for moderate elongations) resulting in a straight line through the origin, and that may be expressed mathematically as $f(x) = ax$, corresponding to Hooke's law in physics. This linear model, however, has a limited domain of validity, because the elastic properties of the jelly change towards the breaking points. Jelly babies with different colours also have different material properties and may give different slopes of the graph. Furthermore, because the elastic properties of the material change when the jelly baby is stretched close to the breaking point, the slope also will change if a new elongation is carried out. During and after the activity, students and teachers were encouraged to emphasise all three levels of understanding mentioned from Ford and Wargo (2012). This means, for example, encouraging the teachers to use the activity for illustrating multiple representations for a science phenomenon, and discussing limitations in these models and why some models are preferred as compared to other models.

The other activity investigated how air resistance depends on the speed when paper muffin cups are falling (Angell and Ekern 1999). Paper muffin cups fall nicely and evenly when dropped, and they very soon reach terminal velocity. Their motion (speed and position) may be recorded using a data logger. Two to five cups may be placed inside one another, forming an object with the same surface but with two to five times the weight of one. Before conducting this experiment, students were introduced to the conceptual ideas and worked on drawing free-body diagrams. They were then introduced to two hypotheses (i.e. two possible beliefs or models) about the influence of air resistance on falling objects of differing masses: (a) that air resistance is proportional to the terminal speed and (b) that it is proportional to the terminal speed squared. These hypotheses were next expressed using mathematical representations. Deductive inferences implies that hypothesis (a) indicates a linear relationship between weight of falling muffin cups and speed and hypothesis (b) indicates a linear relationship between weight and speed squared. Students then conducted the experiment plotting weight (number of muffin cups) as a function of terminal speed and terminal speed squared, respectively, allowing them to conclude that, based on best fit line hypothesis (b) is strengthened as it has the better support in the empirical data. Again, the activity invites students to use representations associated with all the three styles of reasoning in empirical-mathematical modelling (hypothetical-modelling, mathematical-deductive reasoning and experimenting), and to follow the interchange between these. The muffin cups activity is more complex than the jelly babies activity and has a somewhat looser scaffolding. Teachers, therefore, could use the activity in the same way to bring the representations and the reasoning forward as examples for the students, but in a more demanding way and with more requirements for students to use knowledge and skills learned from the previous activity.

The two modelling activities illustrate the concept of empirical-mathematical modelling, with students constructing a mathematical model describing a specific phenomenon based on collected data and established theory (notably Newton's laws) by using a range of representations. Students analyse a physics phenomenon, identify relevant variables, based on the theory, and use experiments and mathematical tools to determine a relationship (the model) between them. Last, but not least, they have to carry out an argument about quality of the data and how certain they can be about the final conclusion. Consequently, emphasis is put on making the various representations of the phenomenon clear to students and helping them develop a perspective on physics knowledge and reasoning. Indeed, the relationship between mathematics and physics is highlighted, and there is a focus on scientific reasoning related to experimental results, particularly by formulating hypotheses and testing them experimentally.

Throughout the physics course, teachers were encouraged to use modelling exercises when introducing new concepts from the textbook. Teaching motion with constant acceleration, for example, teachers could start with an experiment, followed up by interpreting the results using graphic representation and then constructing a mathematical model. Students could start from experiments such as rolling a wheelbarrow at constant speed with students placed with stopwatches along the track, or rolling balls on the floor and on inclined planes. Although the outcomes for these experiments are given in the textbook, the purpose would be to make students proficient in using the representations and reasoning in empirical-mathematical modelling and to improve their epistemological understanding about physics knowledge. Hence the formula in the textbook could be seen by the students not only as equations but as mathematical models. Teachers also could use the activities as a comparison to discuss and evaluate formulas and laws in the physics curriculum even if they were not being developed in activities.

Teachers were also introduced to ICT tools and encouraged to use these in the modelling activities. Among the tools were simulations, or physlets, developed to illustrate physics phenomena and theories, and graphical and mathematical tools in data logging and spreadsheet software. We also introduced the software Modellus (Teodoro 2002), which has been developed for students to investigate science phenomena through their own model-building and to use mathematics to create and explore models interactively. The software explicitly makes use of multiple representations, as the data screen at the same time shows a phenomenon (as an animation), the model (as one or more mathematical equations) and graphs representing position, speed etc.

Lastly, teachers were encouraged to use project work where students could perform comprehensive, open-ended experiments with little or no scaffolding in order to elaborate empirical-mathematical modelling independently and more extensively. These activities would be used after students had conducted several structured activities (Bradley 2005).

2.4 Methodology

The methodology in PHYS21 was based on design research (Barab and Squire 2004; Kelly 2003), which aims to produce not only new theory but also artefacts and practices that potentially may impact learning and teaching. The research rationale takes into account the complexity of real-world practice, with the social context being a core focus and not an extraneous variable to be trivialised. Furthermore, participants are not regarded as subjects assigned to treatments but rather co-participants in designing the research. This means, we worked closely with teachers, in particular in the first period of the project, to develop ideas and teaching material and trialling these in the classrooms. We also allowed freedom to teachers for how the intervention material was implemented and used, and tried to learn from this variation. In the final stage of the research, however, we made a more direct comparison between experimental and control classrooms, which were selected from demographically matching schools not participating in the project. The project, therefore, combined perspectives from different research paradigms (Treagust et al. 2014): it used an interpretivist paradigm by studying in detail ways students and teachers developed understanding and practices, and combined this with a positivist paradigm testing effects of the intervention material. It also used a critical paradigm by focusing on the social actions and reasons for change, or resistance to change, in the project.

The full project took place over a period of 3 years. The first year had workshops with teachers to develop the rationale and design teaching and learning activities. The second year was a pilot year primarily to test the activities and explore ways of implementing the pedagogy. The third year was a full implementation with systematic data gathering from experimental and control groups.

In the initial phase (two first years), 10 schools, distributed in two geographical regions of Norway, and about 20 physics teachers participated, whereas 6 schools, 13 teachers (2 female and 11 male) and 289 students (17/18-year-olds) took part during the full implementation year, systematically employing the PHYS 21 course material and activities involving empirical-mathematical modelling along with a focus on representations (Guttersrud 2008 p. 146). A total of 240 students enrolled at nine other schools were sampled as a control group. Both groups included urban and rural schools. The total sample was therefore 446 students at 15 schools. Among these were 165 (37%) females. Norway has an egalitarian society with small differences between schools and geographical areas, so even if the project used a non-random sampling procedure, which does not allow statistical generalisation to the population of all physics students in the nation, the study is believed to have value for comparison to most physics teaching.

Data gathering to answer the research questions was carried out in multiple ways (see overview in Table 2.1). A research team, consisting of three researchers and a PhD student, between them visited all project schools to observe teaching activities,

Table 2.1 Overview of data gathering and analysis in PHYS 21

Method	Sample	Analysis
Classroom observations with video recordings and note taking	6 schools, 289 students	Narrative analysis first independently then jointly by researchers to identify themes
Online questionnaires to teachers	12 teachers	Narrative analysis of open-ended questions and use of simple descriptive statistics
Lesson plans from teachers	13 teachers	Narrative analysis first independently then jointly by researchers to identify themes
Notes from discussions with teachers in workshops	20 teachers in pilot phase and 13 teachers in final year	Narrative analysis first independently then jointly by researchers to identify themes
Interviews with teachers	6 teachers	Transcriptions. Then narrative analysis independently and jointly by researchers to identify themes
Questionnaire to students	446 students (289 in experimental and 240 in control group)	Descriptive and inferential statistical analyses using SPSS
Achievement test to students	446 students (289 in experimental and 240 in control group)	Descriptive and inferential statistical analysis using SPSS

which was documented with notes, video recordings and/or sound recordings. After the full implementation year, a short, online questionnaire was administered to the 13 teachers who had been actively involved in teaching. Twelve teachers responded. The questionnaire comprised both open questions and closed Likert-type questions. The 13 teachers in the experimental group were also invited to send in lesson plans, suggested modelling activities, comments and experiences, which were published on a web site open to project participants. Impressions and notes from the discussions during project teacher workshops also constituted a source of data.

Semi-structured interviews with six teachers (one teacher selected randomly in each experimental school) were conducted during the second year of the study (pilot phase), lasting approximately an hour each. In these interviews teachers described their teaching in the project, their interpretations of representations and modelling and what parts of the project they regarded as most beneficial for physics teaching. Interviews were transcribed and analysed qualitatively by three researchers. Although we did not use any systematic coding, themes were extracted from narrative analysis related to mentioned topics and discussed among the researchers. An overview, for example, was made of the teachers' approaches to the teaching and their interpretations of the project aims and rationale. Transcripts were reread to check preliminary interpretations until a consistent account was constructed and agreed upon.

In the final year of the study, students were given a questionnaire and a written achievement test (see examples in Appendix) towards the end of the school year. These are thoroughly described in Guttersrud (2008). The questionnaire asked about use of representations in the teaching, students' learning strategies, views about the nature of science and experience with empirical mathematical modelling. The questionnaire was an important tool for learning about the classroom teaching, as well as students' perceptions of this. The achievement test measured students' understanding of and abilities to apply and interchange between representations in physics problems. We did not use a pre-test, but instead compared initial differences in the means between experimental and control schools using students' science and math grades before entering the physics course. The test and the questionnaire were the only instruments administered to both the experimental and the control group. Data were analysed by forming scales in the student questionnaire and achievement test, and comparing these between the two groups by using effect sizes (Cohen's d). Effect sizes were preferred, partly, because they are easy to interpret, and partly, because the study did not have a randomised sample. As explained by Coe (2002), Cohen's d is calculated without including sample size and is used as a measure of the actual difference between independent samples. The study also used significance testing, but not as a means of testing transferability of findings from sample to population (Crocker and Algina 1986). Because of the non-random sampling strategy, significance testing was used as a means for estimating the probability that a difference or correlation is caused by chance. A significant difference or correlation has a probability less than 5% or 1%, and these levels are given in the results.

The combined use of quantitative measures and qualitative data penetrated all parts of the study. Questions in the questionnaire, for example, were not used just for scales, but analysed individually and compared to outcomes from interviews and classroom observations. More information about the methodology is available in Guttersrud (2008).

2.5 Results

As mentioned, we asked research questions about what happened in the classrooms (RQ1), about teacher's conceptions of physics teaching and the curriculum (RQ2), and about effects on students' learning (RQ3). When presenting the results, we compare data from students' questionnaires across the experimental and control groups and look at classroom observations in the experimental group to answer the first question. The second question is answered by using data from interviews with teachers in the experimental group, and the last question by comparing data from the achievement test in experimental and control group.

2.5.1 Student Questionnaire Data

Data from the student questionnaire revealed two main trends about the teaching. The first trend was an expected increase in focus on representations in the experimental classroom as compared to the control group. This is documented in a series of scales based on the question-pattern "how often does [something] happen in physics lesson", with students answering on a five-point Likert-like rating scale (see Appendix). Table 2.2 indicates frequency of interchanges between different types of representations, e.g. using mathematical representation in combination with one the other representations (the subscales are accordingly not mutually exclusive at the item level). Values are adjusted by dividing the aggregated score by number of items

Table 2.2 Interchange between multiple representations in physics lessons (Guttersrud 2008 p. 65)

Scale (n items)	Cronbach's Alpha	Exp. Group N = 242 Mean (std.dev.)	Control Group N = 204 Mean (std.dev.)	Effect size (Cohen's d)
Graphical (6)	.7	3.2 (.63)	2.6 (.61)	.9**
Experimental (4)	.6	3.1 (.65)	2.8 (.64)	.5**
Mathematical (4)	.5	3.3 (.65)	3.0 (.62)	.5**
Conceptual (7)	.7	3.1 (.56)	2.8 (.58)	.3*
Pictorial (4)	.8	2.3 (.77)	2.3 (.82)	.0

*/**the probability for difference between the groups' mean values caused by chance is less than 1% and 5% respectively

in the scale, which means the scales have values from 1 to 5 as in the Likert scale. Results are ordered by decreasing effect sizes.

As can be seen, all except one scale have positive effect sizes in favour of the experimental group, varying from 0.3 to 0.9. This was a reoccurring pattern also in other scales. The table also shows that the experimental group had mean values at or above the mid-point of the Likert scale, while the control group was at or below the mid-point. Mathematical representation was the most used across both groups, while pictorial representation (including diagrams), somewhat surprisingly, was the least used representation.

The second trend relates to how representations were used in the teaching. Drawing on Mortimer and Scott (2003), questions were divided into two groups whether they asked for authoritative teaching, in which the teacher uses a representation to explain or illustrate a concept, or dialogical teaching that takes students' ideas about the representations into account.

Table 2.3 shows that the experimental group, on average, had slightly higher values on both types of teaching, but that the authoritative teaching only was beyond chance ($p < 0.01$) due to a smaller standard deviation. Further investigation, using an one-way ANOVA test with schools as independent variable showed that dialogical teaching also had differences beyond chance ($F = 4.62$; $df = 14$, $p < 0.000$), but that this was a characteristic of certain schools independently of being in the experimental or control group. Some schools, and thereby some teachers, in other words, across the whole sample seemed to have a more dialogical use of representations. Another scale in the data set, which measured dialogical teaching more generally and not related to use of representations (e.g. asking for the extent to which students discussed concepts, hypothesis, laws and theories in physics lessons), confirmed this picture with a very similar outcome ($F = 6.54$, $df = 14$, $p < 0.000$). There was, however, no contrast between dialogical and authoritarian teaching, as the correlation between the two styles of teaching was 0.4** when scales were aggregated to school level. Some teachers, therefore, seemed to do more of both styles of teaching.

Putting the two trends together suggests that the extent to which representations occur in physics teaching and how they are used in the teaching have to be looked at separately. The amount of representations increased beyond ordinary physics

Table 2.3 Dialogical and Authoritative approaches to teaching different forms of representation

Scale (n items)	Cronbach's Alpha	Exp. Group N = 242 Mean (std.dev.)	Control Group N = 204 Mean (std.dev.)	Effect size (Cohen's d)
Dialogical teaching (10)	.8	3.2 (.58)	3.0 (.62)	.2
Authoritative teaching (27)	.9	3.2 (.46)	3.0 (.44)	.5**

**probability for difference between the groups' mean values caused by chance is less than 1%

teaching in PHYS21, but the characteristics of the teaching had much variation. Details of the latter are difficult to read from the student questionnaire, but the variation seemed to be inherent to physics teaching generally, as it occurred across the control and experimental groups, and not typical to the PHYS21 intervention.

2.5.2 Classroom Observations

Classroom observations shed further light on the characteristics of the teaching. As mentioned, observations were made in the experimental classrooms only and we visited schools mainly when they carried out modelling activities. The results are therefore naturally skewed towards these activities. In the observed classrooms, however, we found three main differences in how modelling and representations were taught. The first difference relates to the explicitness of representations and models. By this we mean that some teachers would use a separate lecture, or part of a lecture, to introduce modelling, and next have students themselves carrying out modelling tasks. The teachers typically would talk about models and representations and how these relate to physics knowledge and methods. Other teachers omitted this explicit introduction and instead used the student-based modelling activities indirectly to introduce empirical-mathematical modelling. This difference was repeated in other lessons and created a contrast between explicit and implicit teaching of modelling and representations.

The two next differences both relate to the communicative approaches described by Mortimer and Scott (2003). We observed dialogical and authoritative teaching, as mentioned in the questionnaire data above, with more or less emphasis on exposing students' ideas in the teaching, but also interactive and non-interactive teaching, with more or less student activity. These three dimensions, i.e. explicit/implicit, dialogical/authoritative and interactive/non-interactive teaching, dominated the observations, but operated somewhat independently and therefore created a wide range of communicative approaches. This made it difficult to evaluate lessons for supporting or not supporting students' learning of representations. Some lessons could provide interactive and dialogical teaching with explicit discussions of representations, but not conclude in clear messages about what students should learn. Much depended on teachers' authority and ability to put forward questions that brought out students' ideas, and to draw discussions and activities to conclusions supported by the correct physics ideas. We observed authoritative/non-interactive lessons we thought had better support for students' learning of physics than dialogical/interactive lessons, because the learning outcome was more explicit and obvious to students.

2.5.3 Teacher Interviews

When asked how they had adopted material from PHYS21, teachers typically expressed personal rationales for physics teaching that to some extent explain observations from the classrooms. There were too few teachers to categorise these rationales systematically and to tell if the particular rationales are common among teachers in general, but the nature of the interaction with the teaching is deemed important. Three teachers will serve as examples. A main issue in each example is how the rationale interacts with the dimensions of explicit/implicit, authoritative/dialogical and interactive/non-interactive teaching.

The first teacher had a rationale that learning physics means learning a "world-view" (his concept), and students therefore should understand characteristics of this particular way of seeing natural phenomena. Meta-analysis, i.e. talking about the nature of physics knowledge, therefore was an established pattern in his teaching before entering PHYS21. He frequently included small class discussions about science methods, evidence in science and socio-cultural aspects of science. When engaged with PHYS21, he could continue this reflection with a focus on modelling and representations:

> As I have said before…it is open what the results will be, so they [the students] are forced to reflect more on physics. This is the way I see it. And you got the ways of presenting results…with graphs and mathematics combined with physics. All this is… trying to see connections.

The rationale naturally invites interactive and dialogical teaching with explicit discussions about modelling and representations. The teacher, however, because he saw nature of physics knowledge as an explicit aim for the teaching, also expressed an authoritative style of teaching with a clear message about what knowledge students should obtain.

The second teacher expressed a rationale that his teaching should "recreate the history of physics":

> ..I think historical physics, the way ideas have developed in physics, is very exciting. It has always been exciting to see how things started. How accidental events have caused progress, but mainly because the scientists have been well prepared.

The teacher illustrated how he brought this rationale into the teaching by copying Galileo's experiments when introducing force and motion: students modelled physical motion through a stepwise series of activities, starting by dropping metal balls and timing them with a stopwatch and next rolling them down an inclined plane to slow down the motion, because the first activity had too much uncertainty. The teaching approach made use of graphs and regressions and the final outcome was the equations of motion as found in physics textbooks. The teacher also had a focus on translation between representations before getting involved with PHYS21. His comment to the intervention material was that this was not something new, but it offered more examples for him to demonstrate how physic knowledge "was created". The rationale, however, invited less dialogical and interactive teaching than in the case of the previous teacher, because each historic example had a fixed structure and outcome. There was also less explicit discussion about nature of the knowledge involved.

The third teacher presented a rationale resembling guided discovery-teaching, describing how he wanted students to "find physics laws for themselves". This, he claimed, was challenging teaching, but the modelling activities in PHYS21 offered opportunities he had embraced, because they guided students to main laws in the physics curriculum. It influenced the way he presented activities to the students:

> They [the students] are supposed to find out something, and I give a very clear message about what the task is all about, but I do not tell them what they are expected to find.

The teaching, as a consequence, had little explicit discussion about the nature of knowledge. The teaching appeared interactive and dialogical, because students should "find something out", but the tools and arguments students used in this process were subordinate. The main issue, for the teacher, was that students in the end "got the right knowledge".

These rationales aligned with observations from the classrooms. We could observe how each of the teachers acted out their rationales, and how this influenced the three mentioned dimensions of the teaching. More information about teacher rationales how these made teachers adjust and adapt the intervention material is found in Angell et al. (2008).

2.5.4 Students' Achievement Test

Students' achievement was measured in a post-test only, using students' average grades in science before entering the course as evidence that there was no pre-differences between experimental and control groups ($t = 0.75$, $df = 400$, $p = 0.45$). The test, which had 49 questions and Cronbach's Alpha 0.74, measured students' understanding of and abilities to use and interchange between different forms of representations in physics problems. As seen from Table 2.4, a somewhat surprising result shows that students in the experimental group did not score higher than students in the control group, as we would expect.

Exploring reasons for this result drew attention back to differences between schools across the experimental and control groups. One-way ANOVA analysis with schools as independent variable shows this difference is significant ($F = 2.35$, $df = 14$, $p < 0.01$) and that the difference between the highest and lowest scoring schools are as much as 1.2 standard deviations, or six times the standard error

Table 2.4 Mean achievement test score for the experimental and the control group

	Mean	N	Std. Deviation
Experimental	21.9	204	7.5
Control	22.0	242	7.1
Total	22.0	446	7.2

Table 2.5 Regression analysis to explain students' score on achievement test

Model	Beta	t	Significance
(Constant)		−.14	.89
Representation-interchange during lessons	−.002	−.04	.97
Dialogical teaching during lessons	−.10	−2.0	.05
Students' NOS score	.16	3.1	.00
Students' science grade	.38	7.6	.00

Adjusted $R^2 = 0.2$, $p < 0.000$. $N = 437$

(means 25.4 and 17.0, SE =1.4). Four variables were then included in a linear regression analysis to explain the test score: the scale for interchange between representations made from the student questionnaire (aggregated to school level); the scale on dialogical teaching in physics lessons in the student questionnaire (aggregated to school level); students' individual score on a scale measuring their epistemic understanding of physics knowledge (NOS Score) based on questions in the questionnaire (see Appendix); and students' grade in science the year before taking part in PHYS21. The results are presented in Table 2.5.

The results confirm that emphasis on representation in the lessons, which was the main characteristic of PHYS21, did not make a significant contribution on the test score. Dialogical teaching has a weak negative Beta value, while the two variables with strongest positive values are students' science grade (before entering PHYS21) and NOS score. The regression model explains 20% of the variance in ability as measured by the achievement test.

2.6 Discussion

PHYS21 aimed at developing teaching material and methods to improve physics teaching and make students better at using and making interchange between representations in physics. The underpinning rationale was to develop scaffolding activities that demonstrated authentic use of representations in empirical-mathematical modelling, and to implement these into the whole physics curriculum. Representations should be made more explicit in the teaching and students should see and experience the role of representations as artefacts in science reasoning and argumentation. According to socio-cultural theory of learning (Vygotsky 1978), students should appropriate knowledge and reasoning from engaging in the modelling activities.

The results have demonstrated that the project was successful in its first aim, i.e. to change physics teaching towards more emphasis on representation. In classroom observations we could observe teachers engaging students in data gathering and interchange between multiple representations of the same physics phenomenon, and the student questionnaire confirmed an increased frequency of interchange between representations in the experimental group compared to ordinary teaching in the control group. The reason for this success, we believe, was much due to the scaffolding activities, which served as useful tools both in communicating with teachers about representations and their role in physics and in implementing empirical-mathematical modelling into the teaching. Teachers were given examples of activities, but also took part in analysing the physics curriculum from a modelling perspective, and we think this analysis had value in itself. Many teachers developed their own modelling activities, or adapted previous teaching material to fit with the idea of presenting physics formula as mathematical models.

Students in the experimental group, however, on average did not improve their attainment in the test of interchange between representations compared to the control group, and this outcome came as a surprise. After having worked with the teachers and observed their successful use of intervention material we also expected improvement in students' attainment beyond that of ordinary teaching, but this did not happen. We did, however, find significant differences between schools independently of being in the experimental group or not. Something, in other words, varied between the teachers and classrooms that was more important to students' attainment score than the influence caused by the intervention. This something caused a difference between highest and lowest scoring schools, both in the control group, equal to six times the standard error. Explaining this difference is therefore important, although, not straightforward.

Three possible factors are indicated by the data. One factor, the science ability of the students, which was measured as their science grade the year before entering PHYS21, had the strongest Beta value in the regression analysis. A possible explanation, therefore, is simply that higher ability students have better understanding of representations in physics, and that this effect is stronger than the contribution made by the PHYS21 intervention material. We know that, although schools are similar, some schools typically recruit more high ability students, and this may have caused the observed differences between schools.

A second factor is students' understanding about physics, which also had a significant positive Beta value in the regression analysis. Previous research supports the claim that students' beliefs about science influence their learning of science (Grosslight et al. 1991; Songer and Linn 1992). We may therefore think that students who have a good understanding about science also understand representations in physics and are better at making the interchanges required in modelling. Again, the data could indicate this is a factor that is more important than the contribution made from the intervention material, and that some schools, and thereby some teachers, independently of being in the experimental or the control, make students develop better meta-knowledge.

The third factor is the teaching methods used in the physics lessons. As mentioned, classroom observations in the experimental group showed variation along three dimensions: teachers would (a) do explicit or implicit teaching of representations, (b) have a dialogical or authoritative style of teaching, and (c) have an interactive or non-interactive style of teaching. All of these, of course, were operating on continua rather than as dichotomies and created a wide range of communicative approaches (Mortimer and Scott 2003). Following Mercer and Littleton (2007) students learn more effectively, and have higher intellectual achievement, when teachers use dialogical and interactive teaching with student-based discussions and argumentation. This would suggest some teachers offered more opportunities for students to discuss representations, but that these teachers were placed equally in the control group as the experimental group. The surprising result, however, is that dialogical teaching, measured in the student questionnaire, had negative correlation in the regression analysis as a variable to explain students' attainment score. This factor, therefore, needs further explanation.

Based on the classroom observations, we believe attention should be drawn towards explicit versus implicit teaching of representations, and how this fits with a widespread authoritative teaching in ordinary physics lessons. Many physics teachers have a successful authoritative style of teaching, in the sense that the teaching is well structured and they communicate explicitly what they want students to learn. PHYS21, somehow, challenged this tradition by introducing the scaffolding activities. Teachers were encouraged to use a more interactive teaching and have students collect data to develop and test mathematical models. Leaving their traditional authoritative teaching, however, many, if not most, teachers had difficulties drawing the same explicit attention towards the learning outcome. This could have happened in the student-student and teacher-students dialogues, which was encouraged in the project, but this type of teaching is demanding and takes a long time to develop (Osborne et al. 2004). The consequence, therefore, was the same problem as experienced in practical work teaching more generally (Abrahams and Millar 2008): the teaching became successful in the terms of making students do what they were intended to do, but not in terms of reaching the intended learning outcome. Teachers, in contrast, who maintained a more traditional authoritative teaching, had more success, and this applied to teachers in both the experimental and control groups.

We should, of course, recognise that some teachers handled dialogical teaching quite well and, in our view, drew sufficient explicit attention towards representations and empirical-mathematical modelling. Although relying on anecdotal evidence only, we believe this was influenced by their personal rationales for physics teaching, as revealed in the interviews. These rationales, however, were established before teachers attended PHYS21, and were likely to vary as much between as within the experimental and control groups.

A main conclusion, therefore, to PHYS21 and its attempt to change teaching towards more and better teaching of representations in upper secondary physics is that teachers need more support to operationalise the intended learning outcomes in their teaching. The project could seem to suggest that using an authoritative style of teaching is better than allowing student to engage in scientific reasoning and argumentation using representations in empirical-mathematical modelling activities, but this, we think, is simply because the authoritative teaching is what teachers currently handle best. A main problem in maintaining this style of teaching, however, is that it only will obtain the two lowest levels in Ford and Wargo's (2012) categorisation of the students' learning. Students may learn to explain a natural phenomenon using a range of representation, and they may learn that a representation is one among a multiplicity of alternatives, but they will not learn to reflect critically on scientific ideas. This level of learning requires dialogical interactions with peers and experts (McAlister et al. 2004).

Besides working with teachers to reflect on and adapt their rationales for physics teaching and improve their management skills to handle dialogical teaching, we therefore think a next step in this research strand should be further development of the scaffolding activities. These activities proved very useful for operationalising, communicating and implementing representations and empirical-mathematical modelling into physics teaching, but not for stimulating dialogical teaching. This could be changed by having more reflective questions included in the activities. Students, for example, could be given data and physics models and asked to evaluate and critique these. Having activities not including data gathering, or organising discussions after students have finished working in the laboratory, makes it easier to direct students' focus towards theoretical and epistemological discussions (Kind et al. 2011). Emphasis should be on making students construct arguments for why certain models are preferred over others, and this reasoning will still require full use of representations available in the physics domain.

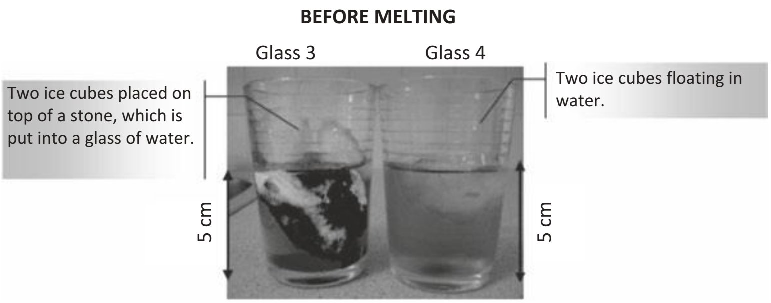
Appendix

Achievement Test to Measure Understanding of and Transitions Between Representations

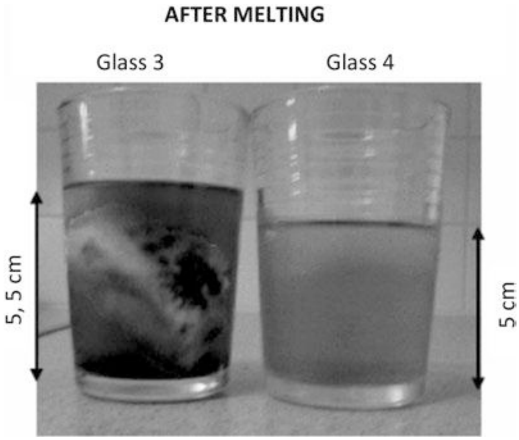
Items in the achievement test (Guttersrud 2008) were organised with a stem followed by 3–8 questions. The following is an example of an item to assess the interchange between an experimental and a mathematical representation of a physics phenomenon (one question included only).

Some pupils wanted to examine how the melting of ice at The South Pole and in the areas around The North Pole influences the sea level.

The pupils put a stone into a glass (glass 3). The stone was supposed to represent the land beneath the ice on the South Pole. They filled the glass with water until the water level was 5 cm. They placed two ice cubes on top of the stone. The pupils filled an identical glass (glass 4) with water. After they had put two ice cubes into the water in glass 4, the water level was 5 cm there as well. Glass 3 is a model of The South Pole, while glass 4 is a model of the area around The North Pole.



After the ice cubes had melted, the following picture was taken:



Assume that the ice is melting at a constant rate. What mathematical model describes the water level (y) in glass 3 and glass 4 while the ice is melting?

A. Glass 3: y = b glass 4: y = ax + b
B. Glass 3: y = ax + b glass 4: y = b
C. Glass 3: y = b glass 4: y = ax
D. Glass 3: y = ax glass 4: y = b

Student Questionnaire

The student questionnaire (Guttersrud 2008) asked questions about use of representations in the teaching, students' learning strategies, views about the nature of science (NOS) and experience with empirical mathematical modelling. The following example shows three questions in a scale surveying the use of multiple representations in physics lessons. Student responded on a five point Likert scale with the response categories "never, seldom, sometimes, often and very often". Each question asks for the occurrence of the teaching focusing on interchange between two different forms of representations.

How often does some of this happen in <u>physics</u> lessons?

(a) Use a data animation to illustrate the relation between the quantities which form part of a formula
(b) Carry out an experiment and represent the data graphically
(c) Use graphs to illustrate concepts

In total 37 questions similar to these examples were included in the questionnaire. Some, as in the examples above, asked for interchange between different representations and others asked for use of single representations. Five different types representations were involved. Thirty three questions asked about students' understanding of the nature of science. These used statements such as "Scientists in physics use creativity and imagination" and students responded on a four-point Likert scale (Disagree, Disagree somewhat, Agree somewhat, Agree).

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Chapter 3
Integrating Computational Artifacts into the Multi-representational Toolkit of Physics Education

Brian E. Gravel and Michelle H. Wilkerson

Computational artifacts such as simulations and visualizations are important representational tools in physics and physics education. But as with any representation, the meaning of a given computational artifact is not immediately transparent, and we cannot expect each individual to interpret it the same way. Instead, computational artifacts are constructed, used, and adapted over time by particular learning communities for particular purposes. Community members must negotiate how such artifacts should be understood as representations that can describe and uncover particular aspects of scientific phenomena. It is this process we are interested in: how *computational artifacts* (e.g., simulations, visualizations, scripts[1]) become meaningful *representations* or *models* of scientific systems as a community works to make sense of those systems. Exploring and supporting the processes by which such shared understandings develop is critical at a time when science educators are expected to engage learners in increasingly collaborative, computational, professionally authentic forms of science.

In this chapter, we address the question: How does a learning community integrate a particular computational artifact into the shared multi-representational toolkit they use for communicating and reasoning about scientific phenomena? We explore this question using two case studies. In one, professional scientists and mathematicians take steps toward developing a new computational "solver" that allows them to create models of the dynamics of liquid crystals. In the other, a fifth

[1] Text computer code intended to be executed in a given computational environment is often referred to as a *script*.

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grade classroom discusses a student-generated simulation of the formation of clouds. In both cases, development of a shared understanding of the computational artifact involved (1) Working to articulate the representational meaning(s) of the artifact and its connection to other more familiar representations; (2) Using shared language about the artifact to focus attention on the causal mechanisms describing the phenomenon of interest; and (3) Noting limitations of the representational artifact and its computational architecture. These similarities emerged even though the epistemic goals of the two groups were different: the scientists sought to efficiently predict liquid crystal dynamics in multiple dimensions, the students to visually reproduce weather patterns.

This process of integrating a computational artifact into a toolkit of disciplinary representations holds implications for educational theory and practice. In terms of theory, we argue that not enough attention has been granted in the literature to how communities of learners make sense of computational representations as tools for communicating and reasoning. Our findings suggest this process is nontrivial, and critical for computational models to be deeply and meaningfully integrated into classroom-level scientific activity. In terms of practice, these preliminary findings point toward patterns of interaction that educators should attend to and encourage when integrating computational artifacts into their classrooms.

3.1 Background

There is a major effort to shift science education from an emphasis on facts and memorization toward an emphasis on construction of knowledge using the tools and practices of science (e.g. National Research Council 2011). Scientific argumentation and modeling have become a major part of what advocates suggest should be practiced in the science classroom (Kuhn 1993; Lehrer and Schauble 2000; Windschitl et al. 2008). But while building and using computational representations (e.g., Mathematica notebooks) is a critical part of professional practice in the sciences, still little is known about how learners develop the shared understandings needed to use them to argue and co-construct knowledge together in the classroom. This is important so that learners understand the epistemic and communicative power of a given computational representation, and its relationship to other representations used in science. Because these understandings take effort and negotiation, it is important that their development be systematically supported in classrooms.

3.1.1 Computational Representations in Scientific Practice

In scientific practice, argumentation and modeling go far beyond the spoken word. They fundamentally involve and are influenced by multiple forms of representation: from informal gestures that highlight structures or interactions, to the use of mathematical languages such as calculus, and diagrammatic conventions that specify or reveal patterns (Kozma et al. 2000; Ochs et al. 1996). From this perspective, these practices are understood to include the discourses between individuals and between the individual and "the material, symbolic, and technological resources in their environment" (Kozma 2003, p. 206). Representational tools, thus, play a central role in the how knowledge is generated, expressed, and shared to construct the "language of communication" for the ideas relevant to that community (Noss et al. 2007, p. 381). The situation is no less true in science classrooms, where the growing use of multiple representations can fundamentally shape how learners interact with one another and co-construct knowledge (Jewitt et al. 2001; Prain and Waldrop 2010). All of this activity requires an understanding of how learners interpret, construct, and negotiate meaning across these various representational resources (Jewitt 2008).

Some of the most powerful and ubiquitous modes of representation in physics are computational (Thijssen 1999). These allow the behaviors, relationships, and/or data associated with a given system to be expressed or manipulated using a symbolic language that can be executed on a computer. When executed, these rules simulate the system of interest, allow users to explore how changes in some parameters of the system affect others, and perform computational manipulations and approximations. These representations offer practitioners opportunities to quickly prototype and evaluate conjectures. And, like equations or other forms of formal representation, computational representations are highly specific, sharable, and revisable by others (diSessa 1995; Wilensky and Rand 2007).

Despite their popularity, exactly *how* computational artifacts are meant to serve as representations in science practice is unclear, and varies from community to community (Grüne-Yanoff and Weirich 2010). Scientists and philosophers of science are still working to understand how computational models might (or might not) be used to productively represent real-world systems, or to represent theory about those systems and their inner workings (Grimm et al. 2005; Peck 2012). Thus, establishing the scientific utility of these computational artifacts is both a matter of personal judgment (Winsberg 1999) and collaborative meaning making among colleagues (Chandrasekharan and Nersessian 2014).

3.1.2 Computational Representations in Science Education

Given their centrality in contemporary scientific practice, many researchers have started to explore how computational representations might be used in science education. Most of this work has focused on the construction and use of simulations to promote learning in particular domains such as ecosystem dynamics or Newtonian physics (Clark et al. 2009; Hilton and Honey 2011; Perkins et al. 2006). Here, we limit our focus to studies that have explored the construction and/or use of computational representations primarily as a way to engage learners in the practices of scientific argumentation and modeling.

One approach to using computational representations in classrooms involves developing software tools and curricular sequences that engage individuals or small groups of students in building their own computational models to generate and test explanations and arguments. Stratford et al. (1998) documented what they called "Cognitive Strategies for Modeling"—analysis, relational reasoning, synthesis, testing and debugging, and making explanations—that they argue students engage in while building dynamic computational models. Others describe similar phases of construction, analysis/exploration, and evaluation as critical for engaging in argumentation through computational construction (Clark and Sengupta 2013; Ergazaki et al. 2007). Xiang and Passmore (2014) documented how learners reasoned about a phenomenon, articulated understandings of that phenomenon using program code, and evaluated the resulting artifact in a cyclic and interwoven fashion as they constructed and revised simulations of natural selection. However, less work examines how such artifacts might afterward be used at the classroom level to support collective argumentation and knowledge construction.

A second line of work engaged large groups or whole classrooms in argumentation using data and evidence from scientific simulations. Much of this work focuses broadly on pedagogical and discursive patterns in the classroom (Smetana and Bell 2014; Hennessey et al. 2006), rather than the specific roles simulations are expected to play in learning and knowledge construction (Greca et al. 2014). However, there is some evidence that working to understand the meaning of a given computational representation is nontrivial. Berland and Reiser (2011) found that some middle school students blurred the distinction between inferences and evidence when engaged in scientific argumentation using a computer simulation of ecosystem dynamics. They believed that differences in graphs within the simulation reflected fundamentally different computational rules rather than randomly-generated variation. Those students who *did* attend to the distinctions between inference and evidence tended to construct more persuasive arguments for their peers. Hmelo-Silver et al. (2015) described how two teachers engaged their students differently in simulation-mediated inquiry. They found that one teacher, Mr. Fine, encouraged students to explicitly reason through what particular features of the simulation were meant to represent. The authors noted that this approach was likely to help students use the technology for reasoning and knowledge construction, rather than only for content acquisition.

3.1.3 Computational Representations as Distributed

In this chapter we bring together the two lines of work described in the previous section. We are interested in studying communities in which members construct their own computational artifacts, and in the ways those artifacts then become understood, shared, and integrated into the representational toolkit of the community as a whole.

To better understand this point of intersection, we draw on the notion of *distributed representations*. Distributed representations are "… created and used in the cooperative practices of persons as they engage with natural objects, manufactured devices, and traditions, as they seek to understand and solve new problems" (Osbeck and Nersessian 2006, p. 144). Osbeck and Nersessian interpret the distribution and use of representations as involving two notions they termed *cognitive partnering* and *representational coupling*. Cognitive partnering involves forming links across people and artifacts in order to allow or sustain sense-making practice. For example, researchers may note that they are building on colleagues' prior ideas or work. Or, they may grant agency to particular artifacts—for example, by suggesting components of a physical model want to behave a particular way—as they come to view those artifacts as partners in thinking. Representational coupling involves articulating relations across multiple representational resources, so that those resources form systems that can be used as models for reasoning.

The work of Osbeck and Nersessian (2006) was conducted in the context of biomedical engineering laboratories involving, primarily, physical representations. However, their account offers insight into our own question about computational representation in knowledge communities. In many research collaborations, such as the one we describe below, a subset of members of a team create a computational artifact. The artifact is to be used meaningfully by the wider team, with the intention of moving forward the collective work. And in classroom communities, there is increasing interest in developing shared epistemic and representational practices to move forward students' work (Enyedy 2005; Greeno and Hall 1997). These processes of partnering and coupling with computational artifacts are critical in order for those artifacts to become distributed representations that allow the community to move forward.

3.2 Research Design

This study was conducted as part of the NSF-funded project entitled SiMSAM: Bridging Student, Scientific, and Mathematical Models with Expressive Technologies (henceforth the SiMSAM Project; IIS-12172100). One goal for the project is to better understand what authentic computational modeling practice might look like in middle school science. We did this by developing and researching how students use a simulation construction toolkit (henceforth SiMSAM for *Si*mulation, *M*easurement, and *S*top-*A*ction *M*oviemaking; Wilkerson-Jerde et al. 2015), and by consulting with, and studying the behavior of, professional scientists who use computational modeling in their own work.

Our research design is most closely aligned with an interpretivist paradigm that seeks to acknowledge and work from the "localized meanings of human experience" (Treagust et al. 2014, p. 7). Building from a design-based research perspective (Brown 1992; Collins 1992), we seek to develop theory about modeling with representational toolkits by designing a tool (i.e., SiMSAM) that allows us to iteratively examine that theory over cycles of engagement. We do not attend explicitly to "culture" in ways others within this paradigm have done, but we carefully consider contexts—e.g., a research group, a particular classroom—as places with specific conditions, from which we hope to develop descriptions of theory that explain the dynamics we observe. Further, the standards for quality research within interpretivist paradigms overlap with those of DBR in valuing sustained and prolonged interactions in the field, careful, repeated sifting through data, reflective analysis of data, and clear and rich reporting (p. 9).

3.2.1 Study Context

The question we put forth in the introduction to this chapter was: *How does a learning community integrate a particular computational artifact into the shared multi-representational toolkit they use for communicating and reasoning about scientific phenomena?* We pursue this question through a comparative case study of two learning communities with different goals – one more professional, and one more pedagogical. For each, computational models served a central role in mediating how participants communicated and reasoned with one another about physical phenomena. We conduct a descriptive multiple case analysis with these two complementary cases for the purpose of theory-building.

3.2.2 Professional Scientists: The LCD Research Group

The LCD Research Group was a collaboration of theoretical physicists, computational mathematicians, and mechanical engineers. Two principal investigators in this collaboration were disciplinary consultants for the SiMSAM Project, which provided us with knowledge of the nature of their work, specifically, that computational modeling played an important role in their research. The group sought to model the behavior of liquid crystal structures, which could in turn inform the development of faster and more energy-efficient liquid crystal displays. Their work involved extending established 1-dimensional and 2-dimensional models of liquid crystal behavior to more complex, multi-dimensional cases. Such extensions had been previously difficult. The governing mathematical descriptions of the phenomena (based on the Ericksen-Leslie equations, Lin and Liu 2000) were often too complex to solve analytically and most computational algorithms were inefficient and expensive to operate. The group sought to leverage recent advances in the algorithmic design of computer-based mathematics "solvers" to develop more efficient models.

We asked to video record a research group meeting to gain insight into how computational models are discussed and used as a part of professional scientific work. We collected data during a meeting early in the collaboration. Four people were physically present at the meeting, and one attended via Skype projected on a laptop.

Fig. 3.1 Cameras were positioned to capture the LCD Group's face-to-face and Skype interactions. One camera was directed to capture gestures and written artifacts in detail

Brian (author) attended the meeting. He used one video camera on a tripod to capture the whole group's conversation and interaction, and a second hand-held camera to capture the gestures and sketches participants made over the course of the meeting (Fig. 3.1). He also interviewed Ian, the theoretical physicist, after analyzing the video episodes to gain further insight into the goals, purposes, and activities of the meeting.

3.2.3 5th Grade Science Class: The Evaporation and Condensation Lesson

The SiMSAM research group partners with classroom teachers to enact scientific modeling activities. During the activities, middle school students use computer-based animation and simulation tools to construct models of "experiential unseens" (Gravel et al. 2013, p. 165), such as smell diffusion or air pressure. In this chapter, we report on data collected from one such enactment with a fifth-grade class in an urban public K-8 school in the northeastern United States. This class was one of two taught by a collaborating teacher who was already familiar with the SiMSAM project, and had completed professional development focused on computational modeling in the elementary school classroom. Both classes were socioeconomically, racially, and linguistically diverse, and students in the classes were accustomed to puzzling about science questions, volunteering theories, and challenging one another's ideas. We focus on this classroom specifically because of the time and energy spent on the development of a consensus model; in the other class from this sample, more time and energy was devoted to distinguishing between different competing models, leaving less time for the development of a final consensus model.

The two–week activity was designed to focus on evaporation and condensation as related to the particulate nature of matter. For the first week, students addressed the question "When you take a cold bottle of soda out of the fridge, why does it get wet after some time?" and for the second, "What happens to puddles on a hot day?". During both weeks, students were first invited to discuss their theories as a class and

Fig. 3.2 The SiMSAM modeling environment interface, illustrated the program-by-demonstration and menu of options command features. Shown on the *left*, program-by-demonstration is using the "Move" command in one of the menus. The user moves the object some distance, and the program records the relative distance and position of that motion as a translation rule governing that object's motion when the simulation is run. Shown on the *right*, interactions between objects are programmed using the "When I bump..." command, whereby the user selects the two objects to consider in the interaction and sets the rules for how they behave once they come in contact with one another

to create drawn models. Next, they worked in groups of 2–3 with SiMSAM and a desk-mounted camera to create stop-motion animations using common craft materials. Students could then crop images from their animations, which became programmable entities. Finally, they used these entities to create computational simulations representing the processes of condensation or evaporation using a simple, programming-by-demonstration and menu-based programming options (Fig. 3.2). Periodically throughout the sequence, students reviewed one another's animations and simulations in small groups and as a whole classroom, usually lead by their teacher Mr. Arbor. We video-recorded all classroom-level and group-level interactions, as well as on-screen and on-board activity. Our analyses in this chapter focus on video data and transcript episodes in which each group (the collaborators and students) worked together to make sense of a shared representational artifact.

A main goal of the SiMSAM project is to engage learners in their own scientific modeling process, similar to descriptions of model-based inquiry (e.g. White and Frederiksen 1998; Windschitl et al. 2008). As such, we expect that students may not immediately generate a model that exactly replicates or aligns with scientific convention. Instead, it is students' progress and ways of revising their generated models to become more coherent, explanatory, and predictive that are the focus of our work. (For a detailed account of the motivations for this sequence and ways in which learners iteratively present and revise ideas, see Wilkerson-Jerde et al. 2015.) The diversity and variety of student models of evaporation and condensation that were yielded by this approach are a methodological strength for this analysis. It made especially evident different students' interpretations of, and ways of negotiating in order to reach consensus around, the representational meaning of a given simulation.

3.2.4 Analysis

We approached the data presented in this chapter as a descriptive multiple-case study with theory-building as a goal. Our guiding “quintain” (shared phenomenon of interest across instances; Stake 2006, p.4) was the uptake of a particular computational artifact as a shared representational tool. We sought evidence of this phenomenon by investigating episodes within each case where we knew computational artifacts were likely to be used as representational tools (that is, used explicitly as referents to some physical phenomenon of interest). We bounded video segments by identifying instances from that data during which computational artifacts were explicitly taken up, interpreted, used, or critiqued by each group as representations of the phenomena under study.

Next, we analyzed the video segments as holistic single cases (Yin 2009), working to understand each independently. We did this through a process of iterative, collaborative viewing (Jordan and Henderson 1995) during which we took notes and divided episodes into descriptive segments based on major themes. As we elaborated these themes, we identified markers in talk and interaction that we used as evidence that participants had taken up computational artifacts as representational tools. We will describe these themes and markers in further detail below. After working to describe each case independently, we began to draw comparisons and contrasts across the two cases. We complemented these comparisons with additional close viewing. In our presentation of data in the next section, we similarly present each case separately at first and only subsequently identify similarities and differences across them.

Over the course of this repeated viewing, we identified three distinct phases that constituted each case’s development of a shared representational understanding. For both groups, three descriptive segments or “phases” emerged in which participants were: (1) developing a shared understanding of the computational artifact as a representational tool; (2) leveraged the artifact to focus attention on their respective goals; and (3) discussed strengths and limitations of the computational environment relative to those goals. The emergent markers that we identified as evidence that participants were employing computational artifacts as representational tools included *meta-representational talk* (conversation about what symbols or behaviors in the artifact are meant to represent), *articulation of mechanism* (linking between the behavior of the artifact and scientific mechanisms – somewhat like Osbeck & Nersessian’s representational coupling), and *extension of computational architecture* (noting limitations of the software or hardware used to create the computational artifact, or proposing changes to that software). These phases and markers will become clearer, we hope, in the following explication of results; we also describe them in further detail with examples from our data in the Discussion section.

Next, we present transcript excerpts, images, and analysis to illustrate the patterns we observed. In the transcripts, we identify the classroom teacher (Mr. Arbor) and researchers with asterisks to distinguish them from our focal participants, the professional scientists and students. Additionally, we bold-faced sections of transcripts that are quoted and discussed in the analysis narrative.

3.3 Case 1: Modeling Liquid Crystal Displays

We take this case from a research group meeting during which Ian, the theoretical physicist lead on the project, presented a model he generated for group discussion. Ian's role in the collaboration, with his colleague Matthew's help, was to contribute multidimensional systems of equations to describe crystal behavior. Peter, Justin, and John were mathematicians responsible for designing a "solver" for this system of equations based on their own computational algorithms. A mechanical engineer, not present at this meeting, would go on to collect empirical evidence to support their work. The goal of the meeting we focus on here was for all members of the group to understand the basic behavior of liquid crystals, and how those behaviors were typically modeled.

3.3.1 Episode 1 – "It's Just Gonna Lie Down?"

This episode began with Ian showing the group a multi-representational description of liquid crystal behavior in 1-dimension. He generated two 3D plots using Mathematica that showed changes in crystal orientation and fluid velocities (how the liquid crystals move in localized contexts) against time (Fig. 3.3, R1). These

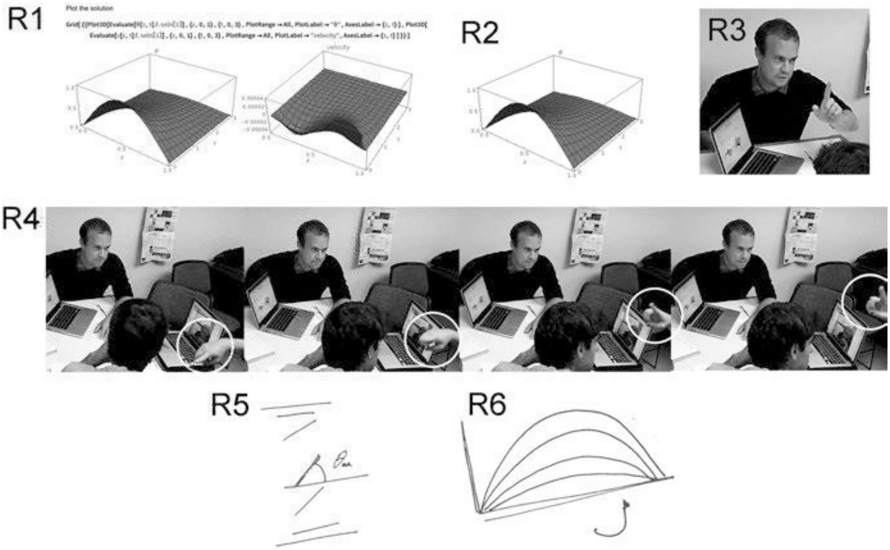

Fig. 3.3 Representational elements from Case 1, Episode 1. R1 shows the example that Ian first presents containing the particular parameters modeled and the 3D plots produced by the computational scripts in Mathematica. This is the central computational artifact for this Episodes 1 and 2 of Case 1

plots, generated by the script written in Mathematica, serve as the central computational artifact for the discussion.

In the plots, liquid crystals were assumed to start in what he called a "distorted state," or "partially switched upward", and moving to a position of rest over time. In a subsequent interview about this episode, Ian likened the crystals to small sticks that either laid flat on a table, or with one end lifted at some angle relative to the surface of the table. He called attention to the first plot on the screen (R2), and used a gesture with his finger to point upwards (R3), illustrating the orientation of the crystal.

Ian So this a first – this is example one.
[*Ian points to R1 displayed on his laptop]*
Its easy to set up all sorts of examples, but this is example
one where you start from initially a **distorted state**,
its admittedly not a very distorted state, but initially quite
a distorted state, and then, so here you're looking at theta.
[Ian points to R2]
So this is – what this would be, is the cell[2] is sort of **partially switched upwards**
[Ian gestures with his finger pointing up, R3]
and then um, we just allow it to relax for a minute.

Peter So **as you go up in Z** I'm going?
[Peter gestures upward with his finger, going from a horizontal position to a vertical position, R4]

Ian Yeah exactly so so, yeah... good job Matthew.
[Ian thanks Matthew and takes pen/paper from him]
So basically here, like that.
[Ian produces a drawing of theta as it changes across the liquid crystal cell, R5]

John Okay alright.

Ian Yea so here – because its not getting all the way up pi over two
[Ian points to peak of 3D plot, R2]
it's only up to a certain point, but you know, it's at **some sort of theta max**. Um and so that's what that graph initially means.
[Ian draws a Cartesian plot showing the front view of 3D plot, where cross sections at different times, t, are sketched on the same plane, R6]
And so the point is that its gonna then **relax over time**, and you can see indeed it does.

Peter And it's **just gonna lie down**?

Ian Yeah it just lies down.

[2] The "cell" referred to by the physicists is a unit of analysis for examining liquid crystals between two boundaries, like in an LCD display. These "cells" have boundaries in one direction, and operate as infinite spaces on the other direction for the purposes of analyzing their dynamics.

Following Ian's initial description of Example 1, Peter re-articulates what he understood the plot to represent. He used a similar gesture to Ian's (R4): a pointed finger moving upward from a horizontal position "as you go up in Z". Ian confirmed Peter's interpretation, and switched from gesture to paper to further clarify what the plot showed in terms of the z-axis, or time. He explained that the highest peak on the plot was "some sort of theta max," which he labeled on the drawing as the point where the crystal was pointed upward at some maximum angle (R5). He drew line segments at decreasing angles to the horizontal, to show the shift in orientation, and drew cross sections of the 3D plot in a graph to show how "it relax[es] over time." Peter confirmed his understanding of the change in orientation over time with a colloquial description, "It's just gonna lie down" as the orientation of the crystal goes from more vertical to more horizontal.

Throughout this episode, Ian connected the computational model he was introducing to a large collection of representational forms—including gesture, sketches, and 2D plots. As Peter worked to understand the 3D plots generated by the model, he appropriated and repeated the representations Ian employed and also offered new, colloquial descriptions. Ian's connecting the novel computational representation to graphs and ideas that Peter already knew well, and Peter's appropriation of Ian's gestures and analogies, are examples of Phase 1–members of the group working to develop shared understandings. This back-and-forth then further allowed Ian and Peter to begin thinking about how different representations would change based on changes in the behavior of the system under study, such as "lying down." This illustrates a shift to Phase 2–focusing attention on specific a particular aspect of the phenomenon, in this case the behavior of crystals. This episode also serves as an instance of the types of representational coupling described by Osbeck and Nersessian (2006) – both across members of the collaboration, and across representational tools.

3.3.2 Episode 2 – "There's Kind of a Funny Bump"

In our final episode, Ian presents a second example to the group that includes a new plot derived from the mathematical model and corresponding Mathematica script. The plot demonstrates what happens when a cell is turned "on," that is, when the liquid crystals are activated or distorted electrically (moving them to the corresponding condition to switching the cell "off" in Episode 1).

Justin	*[Justin is on Skype, and has the Mathematica notebook running on his computer* – Fig. 3.4, *R1]* Could I ask a question Ian?
Ian	Yes, of course!
Justin	So when I look at the, the profile on the left (R2), theta as a function of zeta and t.
Ian	Yep, yep.

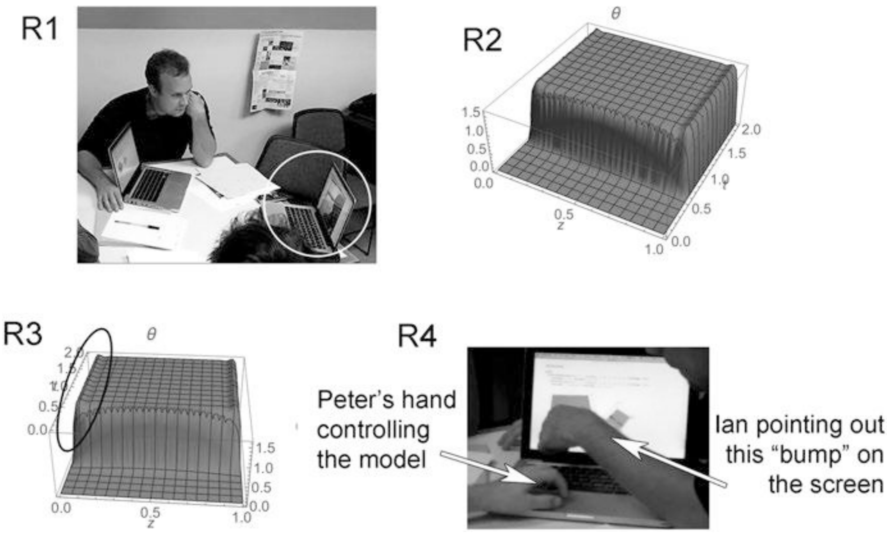

Fig. 3.4 Representational elements from Case 1, Episode 3

Justin If I sort of look at that head on so that the t-axis is going into the page.
[Ian manipulates the plot in the notebook to generate R3]
There's a kind of a **funny bump** around the boundary conditions I noticed…

Ian Yeah yeah yeah yeah yeah

Justin Is that **expected from the physics** or something that we might be guessing as being a **numerical problem**?

Ian I, I wouldn't be at all surprised if its a numerical problem um because um… um… yeah, simply because um I don't think its expected from the physics. Um, that's why I kind of hesitate to say this is sort of a robust test case…

Justin Fair enough, I'm just thinking that if that's saying that theta is going from zero all the way up to pi over two, and then bouncing back right.

Ian He's basically looking at this bump here.
[Ian points to the screen]

Peter I kind of want to look at it now.
[Peter controls the mouse and manipulates the 3D plot – from the top image to the second image to see it "head on" – R3].

Ian	Can you see it? Okay can you look at it head on – yeah can you see that? *[Ian points out the "funny bump" on the plot – R4].* I could actually try and plot it. I could do a cross-sectional plot I'm sure. Um...
Justin	If you did a plot of t = 1, you'd probably see it.
Ian	Would that be useful? I'm not sure—it may, let's see...
Justin	I'm perfectly content with your answer, I just wanted to ask if...
Ian	No no no, I agree with you Justin and I suspect that—that's actually why—I'm glad you raised it because it was actually something I was a little sort of—yeah—it was something I looked at and was like, "I don't know about that." But given that this is obviously a sort of **very generic and nasty solver**. And then the other problem right, there's another problem so, that I'm a little sensitive to, is that, is that there's two pieces in the Mathematica notebook. There's a solver part and that may, may -that may, even if that gives the correct solution, um this then there's then a plotting part, you know. So then its making this fancy 3D plot. We don't actually know **whether that's sort of doing a good job**. So it could either be an artifact of the numerics or of the plotting potentially um. And I agree with you for raising it, because it's **definitely not physical**, so, yup. Yup. And its why we shouldn't take this to – I said this notebook is not intended to be sort of the be-all and end-all um, but it is intended to be a sort of place to start and something of value to everybody to kind of understand at least what's going on.

In this episode, Justin asks whether a "funny bump" on the 3D plot (Fig. 3.4, R2) was "expected from the physics" or whether it was a "numerical problem," resulting from the generic functions within Mathematica that generated the plot. The question leads Peter and others to investigate further by rotating the plot within the computational environment (R3), while Justin suggests generating a new plot at t = 1. Ian explains that the bump most likely arises as a feature of the "very generic and nasty solver" that Mathematica used to generate the plots. That the collaborators "don't actually know whether [the solver]'s doing a good job" reflects the basic difficulties in modeling LCD systems that motivated the collaboration in the first place.

The team's rapid navigation and critique of this new plot reflects their increasing comfort with the computationally-generated plots as representations of the behavior of liquid crystals–another example of Phase 2, focusing on specific aspects of the phenomenon under study. This focus, however, yields an anomaly Their shared understanding is evident in the effortful work they put into distinguishing whether the anomaly Justin noticed was an intentional and predictive element of the representation, or an artifact of the computational tool itself. Ian notes the anomaly in the plot is "definitely not physical," that is, a bad prediction of the physics of liquid crystals. This introduces Phase 3 of the group's uptake of the model, on which they evaluate the role of the computational architecture—the Mathematica solver and plotter—in how the plots may (or may not) be used as tools to represent aspects of the intended phenomenon.

3.4 Case 2: Modeling Condensation and Cloud Formation

Our second case study is drawn from the ninth day of the modeling activities done in one of Mr. Arbor's 5th grade classrooms. This episode begins toward the end of the second week, after students had just finished constructing simulations of an evaporation scenario: What happens to puddles on a hot day?

In the excerpt below, the students had gathered together as a classroom. A simulation constructed by Sergio, Luis and Ryan was projected on a screen at the front of the room. The simulation featured puddles located at the bottom of the screen, small blue objects the group identified as "water droplets" positioned immediately above those puddles, and clouds at the top of the screen (Fig. 3.5A). The students programmed the simulation so that when run, the water particles moved upward in a somewhat random path toward the clouds. When each particle touched a cloud object, the particle would disappear and a new, smaller cloud would appear on the screen near the point where the particle and cloud intersected (Fig. 3.5B).

3.4.1 Episode 1: "What Do We Think About This Representation?"

Students observed the simulation running in SiMSAM, and Mr. Arbor asked the class to comment on what it represented in terms of evaporation and condensation. A discussion with six students follows.

Mr. Arbor*	What do we think guys? What do we think about this, **this simulation, this representation** of it? Sheree?
Sheree	**I think it represents** when the sun evaporates the water, um the clouds they start to make new ones because of the **water vapor**.

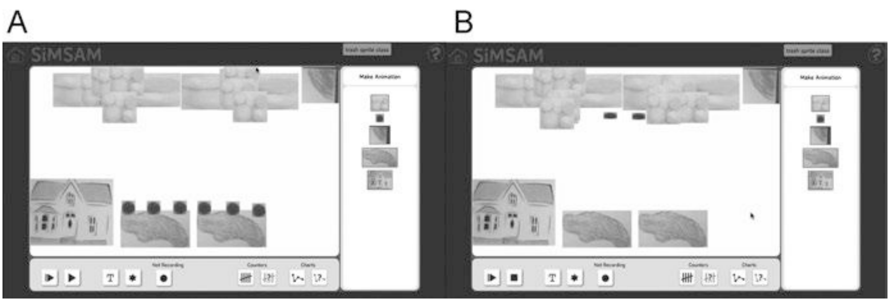

Fig. 3.5 The student generated simulation projected on the Smartboard. In the simulation, "water droplet" objects positioned near puddle objects (**A**) move toward cloud objects. When a droplet intersects a cloud, it disappears and a new cloud appears near the site of intersection (**B**)

Edgar	**I think it represents** because the **water droplets** are **going up**, and then the clouds are getting bigger and bigger because all the water's up, thenwhen it gets full it [gestures down].
Mr. Arbor*	Ok, and that's the next step, if this simulation were to keep going itwould probably show that.
Miles	I think it's just like the **water droplets** are **going up**, and then it's [the cloud] just **gonna get bigger and bigger** and then it's gonna like start getting ready to...
Alan	I think they're trying to represent that the water vapor **forms new clouds**,like more clouds.
Mr. Arbor*	I'm even seeing something, I'm trying to remember if this came up in this class or the other class, like, **when there's evaporation, and it goes into the air, does it form its own new clouds, or does it add on to the clouds that are already here**? So it seems, from what we see here it seems to be adding on to clouds that are already there. That idea was kind of floating around in this room too.
Kenny	First of all I want to say props to you guys – that was really good. And I noticed, and um, I think **the blue little puff balls, they were representing evaporation going up** into the air and every time it hit the cloud it like, it **duplicated** because each every time the little puff balls, **I guess it'd be the evaporation or the water vapor**, it make like a, it added onto the cloud that was already there.
Madison	I think it was really cool that they made that the, when the water vapor hit the clouds that it cloned itself.

In this short exchange, students begin to make connections between the computational artifact—the SiMSAM simulation and its constituent symbols, behaviors, and interactions—and the phenomenon it is meant to represent. In an explicit move to begin Phase 1, developing a shared understanding of the representation, Mr. Arbor asks how students interpret the mapping between the simulation and evaporation as a phenomenon: what they think about "this simulation, this representation of [evaporation]?" Students take this task up, each using phrases like "I think it represents" and "I think they're trying to represent" to describe the simulation's function. Sheree and Edgar establish the meaning of the blue puff-balls as symbols for "water vapor" or "water droplets." Edgar and Miles offer descriptions of how the upward motion of the water droplet objects ("going up") and duplication of the cloud objects ("gonna get bigger and bigger") are meant to represent evaporation and condensation. Alan then touches on a specific mechanism that underlies the water cycle: He notes that the water droplets cause the duplication of clouds when they collide with them, which "forms new clouds."

Alan's suggestion makes space for Mr. Arbor to move to Phase 2, and focus students' attention on a key question about the phenomenon: "when there's evaporation… does it form its own new clouds, or does it add on to the clouds that are already here?" Kenny's response is a deliberate attempt to link the objects in the simulation with the ideas currently under negotiation: "the blue little puff-balls, they were representing evaporation going up." He re-articulates language used in the opening conversation when he says, "I guess it'd be the evaporation or the water vapor." Then, he extends this language to the specific simulated interaction under question, noting that when cloud objects are "duplicated" this suggests clouds are "added onto the cloud that was already there." In his comment, Kenny establishes an explicit connection between the language, objects/symbols, and the ideas represented in the computational artifact. Madison sustains this focus by revoicing Kenny's interpretation using the term "cloned," referencing the specific SiMSAM function used to create the simulation.

3.4.2 Episode 2 – "Maybe You Could Have a Color Option"

A bit later in the conversation, we redirected the conversation to see if there were other representational features or elements students wanted, but were unable to add to their simulations. This initiated Phase 3–an explicit conversation about the limitations of the modeling tool and whether it satisfactorily served the students' representational goals.

Kenny	I know this might not be possible, but maybe, make the color change? I don't know if that's gonna be useful or not, but I'm just saying.
Teacher	What piece would you have change color?
Kenny	The clouds.
Teacher	And talk to me about why.
Kenny	Because when um, when it evaporates, sometimes a cloud gets too heavy then it starts raining, and maybe the clouds get like **darker** or...
Teacher	I remember that from your animation, you guys changed the color of the clouds.
Kenny	So yea, maybe let the color, maybe you could have a color option.
Brian*	So if you were to have a rule, what would the rule be?
Kenny	Like um maybe for the clouds, if I'm alone, maybe say there's like a colorchange there's like a **color scroll thing** there, and you can change the color.
Brian*	So would it just get darker? Or would it get darker if there was... what would make it get darker?
Kenny	Say um like, maybe it could be like um, the blue little, the blue puff-balls like every maybe you could set it so like **how many puff-balls** make it change color?
Madison	Or like **if I bump**, then it will like change color. Like I if you press, or I want the little puff ball, and then it should be another menu saying I can change this color.

In this episode, Kenny proposed a new feature for the SiMSAM environment. Rather than producing a second cloud when a water droplet collides with the existing cloud, Kenny wanted to make clouds become darker in color. We can interpret Kenny's suggestion in more than one way. It could be that Kenny wants better visual fidelity between the simulation and what he has observed in the world. When it begins to rain clouds often look "darker" rather than larger. Or, Kenny's proposal to link clouds getting darker to raining (a behavior that had not yet been added to the simulation) could be a way to chain events together to prompt a re-initiation of the water cycle, an idea the class had discussed in the first excerpt.

Kenny continued with his line of reasoning to propose two additional functions for the simulation environment. One was a "color scroll thing" to change the color. The other was to have the simulations record the number of puff-ball-to-cloud interactions and to control the color based on "how many puff balls" interact with a given cloud. Madison adds that we could do this functionally using the "if I bump" paradigm already present in the architecture of the tool—"bump" standing for interaction between objects. The suggestions not only demonstrate a rich intellectual engagement with the notion of artifact as tool. They also illustrate a firm understanding that the engine underlying the simulation—the architecture of the computational tool itself—can be revised to improve the overall quality of the representation of the model.

3.5 Discussion

The LCD Research Group and 5th Grade Science Classroom we report on in this chapter are quite different learning communities. However, we argue that both successfully adopted a computational artifact as a representational tool. In this section, we draw comparisons between the processes and practices we found in the two cases, and identify specific discursive moves that marked ways in which members of each community begin to treat their respective computational artifacts as representational tools in service of their different goals. We then explore what these comparisons and discursive moves suggest for educators and designers interested in integrating computational representations into physics education.

3.5.1 From Making Sense to Making Use of Computational Artifacts as Representations

The research question driving our work was: How does a learning community integrate a particular computational artifact into the shared multi-representational toolkit they use for communicating and reasoning about scientific phenomena? These two case studies suggest that this process is effortful and explicit. In both cases we examined, we identified three relatively distinct phases of this process of integration.

In the first phase, members of each community worked deliberately and explicitly to develop a shared understanding of the artifact. With the professionals, this unfolded mainly through Ian's articulation of connections between the computational 3D plots and gestures, two-dimensional graphs, and sketches that illustrated the behavior of the crystals modeled. His collaborators indicated understanding by taking up and repeating certain gestures and phrases Ian used, and by testing their own colloquial descriptions of the phenomena. With the students, this process began with Mr. Arbor encouraging his students to explain what they understood the simulation to represent. They first described the visible objects on the screen (like puff-balls), and then with Mr. Arbor's support described what they believed behaviors and rules (such as cloning) expressed within the simulation to reflect phenomenally.

In the second phase, both the professionals and students used the shared language and understandings they had developed to question what each computational artifact implied for events and parts of the system not directly represented. The professionals discussed how fluid velocity extended beyond the single crystal represented in the plots. The students suggested specific ways to incorporate other information about the water cycle into the simulation, such as rain or that water sources reduce in size as they evaporate. Finally, in the third phase, both groups began to identify constraints within the computational architectures used to produce each representation that limited what could be appropriately represented. For the physicists, these limitations became apparent through the appearance of anomalous bumps in plots that did not correspond to expected physical behavior. The students noted that they wished to be able to change the color of objects in their simulation, as a way of increasing either the visual or phenomenal fidelity of their representation.

Upon further analysis, we found these different phases involved three types of discursive moves practiced by both the professionals and the students. These are described in Table 3.1.

Meta-representational talk refers to instances where participants established explicit links between elements of the computational artifacts and aspects of the phenomenon that they are working to understand. This action includes explicitly linking the artifact to other, already-understood representations, or describing what elements of the artifact represent in the phenomenon itself. We see this meta-representational talk as the means by which each group constructed a shared understanding of the artifact. It was also the means by which they developed a shared language around that artifact, such that it could then become a tool for thinking and an object of critique. We view critique as a meta-representational tool (diSessa and Sherin 2000) used to position the artifacts as a useful contribution, but also incomplete, malleable, and fallible. Justin's attention to the "funny bump" and Alan's questioning whether water vapor forms new clouds or builds on existing clouds are examples of critique.

Building on these publicly-established and shared understandings and language, participants then focused their attention on more specific causal mechanisms related to the phenomenon under study. They began to **articulate the mechanisms** that

Table 3.1 Discursive moves practiced as professionals and students worked to make sense and make use of computational artifacts as representations of physical phenomena

Discursive moves	Description	Case 1 Expert examples	Case 2 Classroom examples
Meta-representational talk	Explicit conversation about what symbols, materials, behaviors in the computational artifact mean in terms of the phenomenon under study; and critique of the representational adequacy of the artifacts relative to the phenomena under exploration and the collective knowledge of the learning community.	"So as you **go up in Z** I'm going (Peter gestures upward with his finger, going **from a horizontal position to a vertical position**)?"	"...every time the little puff balls, **I guess it'd be the evaporation or the water vapor**"
		"There's a kind of a **funny bump around the boundary conditions** I noticed…"	"**I think they're trying to represent** that the **water vapor forms new clouds**, like more clouds."
Articulation of mechanism	Establishing links between elements of the artifact and causal mechanisms describing the phenomenon.	"**It's just gonna lie down**"	"...**when the water vapor hit the clouds that it cloned itself**."
Extension of computational architecture	Acknowledging/proposing features of computational architecture supportive or limiting of tool's sufficiency in modeling the phenomenon.	"So then its making this fancy 3D plot. **We don't actually know whether that's sort of doing a good job**. So it could either be an artifact of the numerics or of the plotting potentially."	"Like if you press, or I want the little puff ball, and then it should **be another menu saying I can change this color**."

linked cause and effect, and questioned how these mechanisms were represented within and extended beyond the artifact itself. Peter spoke about liquid crystals just "lying down" and "kicking the water," and Madison proposed that water vapor joins clouds to "clone" new clouds. This serves as evidence that participants used the representational elements and rules to envision new situations.

Finally, both communities began to develop some understanding of the underlying computational architecture that was employed to generate each artifact (Mathematica and SiMSAM). As they developed this understanding, they made suggestions for how to **extend the architecture** to accommodate their epistemic goals. The professionals recognized the need to extend or redevelop the numerical solvers needed to model liquid crystals, indeed one of the major goals of their collaboration. The students proposed a new feature for SiMSAM, the ability to change the color of objects, which would allow them to better approximate the visual features of the water cycle and, perhaps, better computationally illustrate its perpetual nature. This understanding of the architecture underlying the artifact adopted by the community is particularly interesting because it also provides a basis for the community to evaluate and integrate future artifacts into their practice.

3.5.2 Understanding the Representational Toolkit of Physics and Physics Education

Computational tools are an integral part of the toolkit of physics and researchers are calling for increased integration of computational tools in physics education. People have cited a number of functional and epistemic reasons to support this integration. However, increased attention must be paid to these computational environments as representational tools, and how their features can be understood relative to other existing representations, and what specific purposes they are meant to serve.

With both learning communities, the integration of these computational environments into the toolkit of physics is deliberate, explicit, and effortful. At the heart of these integrative processes are learning communities that negotiate shared meaning of an artifact relative to each community's epistemic goals. Variations in process and goals across communities complicate how we think the negotiations of meaning. To understand these dynamics of negotiation and use, it is important to understand and articulate what it is professionals and students are trying to do with these tools in the first place. In our study, we argue there is a difference in the implicit understandings of the goals of these objects for each community. The professionals recognize their model as a knowledge-generating tool; the students focus on accuracy and completeness of their model in representing their understandings of the phenomena. While moments occurred when reviewing their simulations prompted new questions about the phenomena, the students overwhelmingly focused on the adequacy of their representations.

For physics education, these differences highlight that designers and educators may need to explicitly consider what role computational environments, specifically simulations, might play the curriculum: as demonstrations or virtual experiments that students can manipulate, as a medium for communicating one's own understanding of a system, or as a tool to yield new insights into the system under study. All of these goals involve treating a computational artifact as a representational tool that supports thinking and communicating. However, the processes by which this treatment unfolds–negotiation, critique, revision–take time and require deliberate attention to how they are situated within epistemic actions and goals of the learning community.

3.6 Conclusion

One of the most important parts of learning a discipline is learning how to use the tools and language of that discipline required for participation. We argue that computational artifacts are becoming a fundamental component of these tools and languages, and should be treated as such in educational contexts. However, integrating computational artifacts in a way that respects their representational status alongside established forms such as diagrams or equations requires attention and support.

Our findings in this chapter describe the deliberate ways in which two learning communities negotiated a shared meaning for particular computational artifacts. Specifically, we identified three phases and three discursive moves that emerged across cases. Using the notion of "distributed representations" (Osbeck and Nersessian 2006), we contribute more precise descriptions of how computational artifacts become representational tools taking into account the particular commitments of different learning communities. In so doing, we make available these findings for guiding how teachers notice and support the integration of computational artifacts as representational tools in their classrooms. By supporting attempts to integrate these tools, we can tune teachers' attention to the purpose and use of computational representations within the larger multi-representational toolkit of physics and physics education.

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Chapter 4
Evaluating Multiple Analogical Representations from Students' Perceptions

Jing-Wen Lin and Mei-Hung Chiu

4.1 Introduction

Using analogies to promote conceptual change is a common teaching strategy and has been proven effective (Chiu et al. 2016). However, the use of analogies has its limitations. The more complex the concepts are, the more care should be taken by science educators so as to avoid improper use that may lead to students' alternative conceptions. As to how to overcome alternative conceptions, Spiro et al. (1989) propose two methods. One method is to pay more attention to the limitations of an analogy and whether it is misleading or incomplete so as to avoid these complications as much as possible. The other method is to convey more complex conceptions by integrating multiple analogies.

Many scholars, based on theoretical frameworks or their teaching experiences with analogies, discussed the details of the design and teaching of analogies in order to increase the effect of analogies and to decrease the damage brought by the limitations of ill-designed analogies. Related theoretical frameworks include structure-mapping theory (Gentner and Gentner 2014; Wolff and Gentner 2011), teaching-with-analogy (Glynn 1991; Glynn and Takahashi 1998), and focus-action-reflection (Harrison and Treagust 2006). However, Spiro et al. emphasized that it was not enough to just warn students of the limitations of an analogy and advocated for the use of multiple analogies, which can provide students with more opportunities to understand scientific concepts and to shape their misconceptions or alternative conceptions into scientific concepts (i.e., Chiu and Lin 2005; Clement 2008;

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Harrison and Treagust 2006). However, it is worth noting that the use of multiple analogies may result in an increase in cognitive load (Dagher 1995; Shelley 2003; Spiro et al. 1989) or interfere with learning (Gentner and Jeziorski 1990). Since an analogy can be a friend or foe (Harrison and Treagust 2006), ill-designed multiple analogies may cause greater damage to student learning than any single analogy. Therefore, how should we design multiple analogies so that they achieve better effects than a single analogy while incurring no additional cognitive load?

Until now, systematic research and rigorous design principles applied to multiple analogies have been rare. As technology advanced in science education, detailed explanations regarding the design principles for multiple representations used in various technological media were introduced (Ainsworth 1999, 2008; De Jong et al. 1998). Some parts of the design principles for multiple representations even borrowed from the design principles for single analogies (Spiro et al. 1992; Wu and Puntambekar 2012). In general, analogy has been taken as a kind of representation with a special structure (Linsey et al. 2008). Therefore, in light of the abundant fruits of multiple representations research, this study made reference to the literature on multiple representations and a single analogy to propose the design principles of multiple analogies, referred to as the Examination-Analogical Mapping-Transformation (EAT) principle. Basic electricity was used as an example to design learning materials. Although the functions of multiple analogies are many, they can be generally categorized into forming schemas (Holyoak 2005) and overcoming alternative conceptions (Clement 2008; Spiro et al. 1989).

This study designed two corresponding types of multiple analogies in response to the functions mentioned above. Similar analogies were used in student learning of the concept of a circuit by forming analogies between two similar structures to establish schemas. Complementary analogies were used to help students overcome alternative concepts of electricity by forming two analogies with two pieces of complementary information. Our previous studies found that the use of these two types of multiple analogies (i.e., similar analogies and complementary analogies) helped students form schema and overcome alternative conceptions, respectively (e.g., Chiu and Lin 2005). Students' mapping recall accuracy between target and analogical domains also supported that the designed multiple analogies could moderate possible cognitive load (Lin and Chiu 2005). Building on our previous research, this study aimed to evaluate the designed multiple analogical representations from students' perceptions of *analogical limitations*, *personal preferences*, and *cognitive load*. With related discussions, this study provides feedback on the design of multiple analogies in learning materials and teaching in basic electricity.

4.2 Theoretical Background

Analogies are a kind of special representation that contain two aspects: knowledge and format (Thagard 1988). The knowledge aspect is what a student holds to be true without any attempt to explicitly explain the symbols or structures that represent that data. The format aspect overlaps with symbols in that it is influenced by cognitive manipulators and it usually manifests as schemas, propositional networks, mental models, or rules (Rohr and Reimann 1998). The quality of analogical representations has far-reaching effects on follow-up retrieval, use, and learning. However, the research on analogy has placed more emphasis on knowledge (Braasch and Goldman 2010; Gentner and Gentner 2014) while research on representations has placed more emphasis on discussion of format (De Jong et al. 1998) though both knowledge and format are factors that influence analogical learning and complement each other (Schnotz and Bannert 2003). Accordingly, we first propose the design principles for multiple analogies which were enlightened by the research on analogies and multiple representations. We then introduce the frequently used analogies in electricity for the purposes of discussion.

4.3 Developing Design Principles for Multiple Analogies

4.3.1 Enlightenments from Research Approaches to Analogies

Glynn proposed that the quality of analogies could be judged based on the degree to which their analogical targets were achieved. Generally speaking, three conditions should be heeded: the number of traits under comparison between two domains, the level of similarity between things whose traits are under comparison in analogical domains, and the prominence of concepts in analogical domains. The explanatory power of an analogy is mainly determined by the number of similar traits between the analogical object and the target object, which is precisely the structure-mapping-theory emphasized by Gentner and colleagues (Gentner and Gentner 2014; Wolff and Gentner 2011). Nevertheless, a high quality analogy may only have a few similar traits between the analogical domain and the target domain, but these traits have to be directly related to the special purpose the designers want to achieve. Therefore, not all three conditions mentioned above have to be met when designing analogies. The quality of analogies is only judged by whether the target is achieved. This process is similar to the *Action* stage in Harrison and Treagust's (2006) focus-action-reflection guide. In summary, the above-mentioned guidelines required us to pay attention to similarities. However, Podolefsky and Finkelstein (2006) argued that similarities mapping is framed from the experts' point of view, but students' analogical reasoning is changed by different analogical representations. In general, students' characteristics (such as students' experiences, resources, processing skills, and domain knowledge), task characteristics (such as the learning goal), instructional environment, and the framing of analogies are factors that can influence students' perceptions of analogical representations (De Jong and van der Meij 2012; Podolefsky and Finkelstein 2006). These findings highlight the importance of the evaluation of students' familiarity, processing skills of representations, and their perceptions of analogies. This point is similar to the *Focus* stage in Harrison and

Treagust's (2006) focus-action-reflection guide. In addition, Harrison and Treagust also proposed the *Reflection* stage to remind designers to notice the limitations of an analogy.

4.3.2 Enlightenments from Research Approaches to Multiple Representations

In light of the studies on multiple representations in learning technologies, Ainsworth (1999, 2008) offered some insights on how multiple representations are transformed into each other. She pointed out that students have additional cognitive load while making use of multiple representations in their learning: (a) learning additional information related to the format and the operator of each representation, (b) understanding the relationship between multiple representations and the domains represented, and (c) understanding how multiple representations are related among themselves. To effectively decrease the cognitive load, we must consider proper transformation in response to the representational functions expected to be achieved. Ainsworth advocated that the advantages of using multiple representations for learning could be categorized into at least three functions: providing complementary information or process, constraining interpretations, and facilitating deeper understanding. When multiple representations mainly aim for a complementary representation of information or process, the learning environment should automatically show the transformation among the representations, and designers should take into consideration the proper order of representations to facilitate the coordination of representations. Therefore, at this stage, designs concerning the details about learners' understanding of the relationship among representations should be decreased.

When multiple representations are used to constrain interpretations, the second representation is usually designed to support the explanation of the least familiar representation, and no additional information is provided. Here the principle we need to grasp lies in that we do not expect learners to construct the relationship between representations; instead, we hope that they can understand the more complicated representations through exploring the relationship among exhibited representations. The greater the difference is between two representations in terms of format and operation, the more difficult it is for learners to appreciate the relationship between these representations. Finally, Ainsworth proposed to integrate contingency theory into scaffolding as a principle of design when using multiple representations in order to construct students' deep understanding.

In this study, we extended the above-mentioned principles to multiple analogies to simultaneously take knowledge and format aspects into consideration. The functions and transformation principles for multiple analogies are summarized below:

1. When multiple analogies are mainly used to provide complementary information or process, designers should decrease the transformation of analogical representations.
2. When multiple analogies are mainly used for forming schemas based on similarities or unique attributes of analogies, designers should make the transformation of analogies automatic.
3. When multiple analogies are used to promote students' deep understanding, designers should pay attention to how to scaffold the transformation of the relationships between analogies.

On the other hand, de Jong et al. (1998) evaluated the use of multiple representations in a learning environment from five dimensions, namely:

1. Perspective: A special theoretical viewpoint a representation aims to display.
2. Precision: The qualitative or quantitative accuracy in describing a phenomenon.
3. Modality: A special format of displaying knowledge, such as propositions or figures.
4. Specificity: As conveyed by a representation, the special purpose and the special attributes of the representation related to individuals' cognitive skills.
5. Complexity: The level of complexity for information conveyed by a representation.

Among the five above-mentioned dimensions, *modality* and *complexity* clearly connect with the format aspect. As to the other three dimensions, *perspective* is closely related to the knowledge aspect, while *precision* and *specificit*y can be simultaneously used as evaluation criteria in terms of both knowledge and symbols (De Jong et al. 1998).

4.3.3 Evaluation Principles for Designing Multiple Analogies

After reviewing the literature, three stages—Examination for Preparation, Analogical Mapping for each Single Analogy, and Transformation for Multiple Analogies (EAT)—were proposed to evaluate the advantages and disadvantages of the designs for a series of multiple analogies. The details are illustrated in Table 4.1.

According to the literature review (De Jong et al. 1998; De Jong and van der Meij 2012; Podolefsky and Finkelstein 2006), we advocated that, at the stage of examination for preparation, evaluation principles should include *students' cognitive ability and their prior knowledge* and *students' familiarity and perceptions of analogies*. As to the stage of Analogical Mapping for Each Single Analogy," evaluation principles for the design of a single analogy, the main principle was Gentner and her colleagues' (Gentner and Gentner 2014; Wolff and Gentner 2011) structure-mapping theory, aided with Glynn and colleague's (Glynn 1991; Glynn and Takahashi 1998) consideration that high-quality analogies should simultaneously consider the similarities of two domains, the prominence of concepts, and students' familiarity with

Table 4.1 Evaluation principles of EAT for designing multiple analogies

Stage	Evaluation principle	Content
Examination for preparation	**Principle 1**: Examining students' cognitive ability and their prior knowledge	Use questioning, questionnaires, clinical interviews, achievement tests, or a literature review to understand students' *cognitive ability and their prior knowledge*.
	Principle 2: Students' familiarity with and perceptions of analogies	Whether learners have been exposed to the analogies in everyday life and can easily observe them, or whether learners have experienced the teaching that meets the evaluation principles.
Analogical mapping for each single analogy	**Principle 3**: The level of similarity or prominence in terms of structures or attributes between two domains	Structure mapping exists between two domains in terms of objects, attributes, relationship, and higher relationship. Usually the more structure mapping there is, the better. But sometimes we need to consider the level of similarity or conceptual prominence of the unique attributes in two domains in response to the purpose of using analogies. Finally, we have to reflect on the limitations of each single analogy.
Transformation for multiple analogies	**Principle 4**: Representational dimensions of each analogy	Knowledge aspect: Mainly considering *perspective, specificity*, and *precision* in the transformation of multiple analogies. Representation aspect: Mainly considering *modality*, *complexity*, and *specificity.*
	Principle 5: Transfer between representations	Consider the transformation and scaffolding level in response to the functions multiple representations aim to achieve (i.e., complementary information and process, constraining interpretations, or constructing deeper understanding).

analogies and so on. As to the stage of Transformation for Multiple Analogies, integrating Ainsworth's (1999, 2008) principles for the transformation of multiple representations and de Jong et al.'s (1998) classification of representational dimensions, we further probed into the transformation among *perspective, precision, modality, specificity*, and *complexity.* In addition, we suggest that examining analogies' *familiarity* and *complexity* should not only be restrained to the design for single analogies but should also be applied to a simultaneous examination of the five dimensions in the transformation of multiple analogies.

4.4 Frequently Used Analogies in Electricity

The most frequently used analogies in the teaching of electricity are fluid mechanics and imaginary particles (Black and Solomon 1987). Gentner and Gentner (2014) investigated high school students' and college students' spontaneous analogies of electricity and divided students' answers into the *fluid model* and the *moving-crowd model*. According to their findings, the fluid model achieved a better effect on inference pertaining to a battery in a series or parallel connection than for electric resistance; conversely, the moving-crowd model achieved a better effect on inference for electric resistance. Black and Solomon (1987) conducted similar experiments, and they used the straw-milk analogy and the particle analogy in teaching to investigate the influence of various models of analogies on middle school students' concepts of electric current. They pointed out the majority of students used 'flame' to represent electric current before teaching, and they preferred to use particles to explain electric current after being taught. No matter which analogy students selected, those who received analogical teaching all offered better explanations of branch current than those in the control group. Moreover, students' preference for using the particle analogy in explanation, when the teaching was over, was attributed to their inability to fully command the contextual characteristics of the straw-milk analogy.

Schwedes (1984) and Harrison (2008) also noted the value of fluid analogies. Schwedes pointed out the importance of students' understanding the target domain before using analogies. Harrison introduced several water analogies for different perspectives on electricity. A water circulation analogy was appropriate for a simple series circuit; the water pressure analogy was good for presenting voltage, while the shared water flow analogy was best for showing multiple light bulbs and motors in a series circuit. Another analogy concerning fluid is blood circulation. Osborne and Freyberg (1985) discovered that the use of two ammeters in a circuit and the blood circulation analogy helped improve students' understanding of electric current. According to Gauld (1986), children tend to hold on to their consumption model, even "remembering" ammeter readings to support that view.

Some researchers suggest using mechanical analogies, such as a bicycle chain, conveyer belt, or workers pushing a train on a railway (e.g., Dupin and Johsua 1989; Härtel 1982). Härtel (1982) indicated that a bicycle chain is a good representation to help students see the whole circuit as a system. When assisted by an ammeter, students can observe the fact that the amount of current through a resistor remains unchanged. This bicycle chain analogy also helps students become aware that every component will affect other parts and rectifies students' sequential inference model. Dupin and Johsua (1989) used train power, speed of a motor vehicle, and a braking system as analogies for voltage, electric current, and electric resistance, respectively. They found that these designs allowed students to understand that electric currents are just like the speed of a motor vehicle, which remains the same wherever it is and that batteries, just like drivers, consume energy and lose their strength. However, this analogy cannot successfully explain the situation of an open circuit, and comparing vehicle speeds and electric currents may lead to students' over-inference, that is, that electric currents can be calculated by using the formula for calculating vehicle speeds. In addition, from these analogies, students are unable to understand that what causes electric currents is potential difference and that an electric charge stops moving once a conductor has reached the state of electrostatic equilibrium (Mulhall et al. 2001).

The impact of the analogies mentioned above was derived from the viewpoints of experts (e.g., school teachers and physicists). However, what are students' perceptions of these analogies? Do they also agree that the use of these analogical representations is helpful for their reasoning and learning? This study designed multiple analogies based on the design principles (EAT) and explored students' perceptions of conceptual learning, overcoming alternative conceptions, moderating cognitive load, and interest in each designed analogy.

4.5 Method

4.5.1 Participants

This study was conducted in an elementary school in Taipei. Thirty-two average-achieving students were selected from 107 fourth graders based on their scores from an electricity test. The participants were randomly assigned to one of four groups—Single analogy (SigA), similar analogies (SimA), complementary analogies (CompA), or control/non-analogy (NonA). Each group contained eight students. They had not previously been taught the theory of electricity.

4.5.2 Using Design Principles for Multiple Analogies to Design Learning Materials

Four types of learning materials were designed for the four groups: learning material with single analogy, learning material with similar analogies, learning material with complementary analogies, and learning material without analogy.

Five subtopics were considered for the content of the learning materials: a simple circuit, a complex circuit, and an open circuit for the **circuits perspective** and the brightness of a series and parallel connected bulbs and the brightness of the bulb in a series and parallel connected batteries for the **energy perspective**. We designed the learning materials according to the design principles for multiple analogies (see Table 4.1). First, we tried to understand students' prior knowledge of electricity and their developmental condition from the existing literature (**Principle 1**). Then, we listed and considered the dimensions (i.e., *perspective, precision, modality, complexity*, and *specificity*) of each potential analogical representation (**Principle 4**). For example, some potential analogies were selected for their knowledge **perspectives** (i.e., circuits or energy) and special purposes (**specificity**) of the analogical representation. From the literature review, we found that when explaining the circuit, the more commonly used analogies were the 'simple water circulation' analogy and the 'particle' analogy. In particular, the fluid analogy achieved a better effect on inference for current direction; conversely, the imagery particle analogy achieved a better effect on inference for electric resistance (Black and Solomon 1987; Gentner and Gentner 2014). In accordance with Gentner and Gentner's (2014) study, concepts in the electricity domain were further categorized into object, attribute, relationship, and high level relationship (**Principle 3**). Referencing not only the mapping concepts in Table 4.2 but also Glynn's (1991) criteria for judging the quality of analogies, we selected appropriate analogies considering factors such as the analogy's frequency of use, students' familiarity with the analogical objects, possible limitations of the analogical objects, and so on (**Principle 2**). Therefore, we selected the 'simple water circulation' analogy for the SigA group (see Fig. 4.1a). For the same reason, we selected the 'particle' analogy for the SimA group but modified the 'particle' analogy into the "obstacle race" analogy (see Fig. 4.1b), upon comparing students' familiarity with these two analogies (**Principle 1**). As to complementary analogies, they mainly attempted to explain two **perspectives**: the circuit and energy. As a circulating water wheel model is more often used when explaining the concept of energy (Lechner 2012; Taber et al. 2006), this study adopted 'upright and closed water wheel system' (we call it 'complex water circulation'; see Fig. 4.1c).

When possible limitations of these analogies were stated in the literature, we designed appropriate representations (figures) in advance to remind students of these possible limitations (**Principle 1, Principle 4**). For instance, in the case of comparing an open circuit to an obstacle race, being influenced by the sequential inference model, students may assume that electrons (runners in an obstacle race) will pile up at the breaking point in a short circuit (will remain on a broken single-plank bridge; Arnold and Millar 1988; Cohen 1984; Duit 1984; Tiberghien 1983). We used the representations in Fig. 4.2 to outline the limitations of the obstacle race analogy (**modality**). This also resembles the situation in which players are unable to race when a single-plank bridge connected in series is broken (see Fig. 4.2).

When it came to designing learning materials with multiple analogies (SimA group and CompA group), we took into consideration Ainsworth's (1999, 2008) advice on multiple representations (**Principle 4, Principle 5)**. As far as similar analogies learning materials were concerned, because the aim of using similar analogies is to form schema to constrain interpretations, we attempted to make the transformation of analogical representations automatic. In this regard, we thought two similar analogical representations should represent equivalent things in terms of *perspective, precision, modality*, special purpose conveyed (*specificity*), and *complexity*, so as to make the transformation of those analogical representations less difficult. Moreover, two formats of representations (*modality*)—words and figures—were used to facilitate students' automatic transformation of representations, which was mainly achieved by parallel representations of explanation words or figures, as well as the precise correspondence among explanation words and figures.

Table 4.2 Mappings between domains of electricity and analogies

	Domain of electricity	Simple analogies (SimA) Single analogy (SigA)	Complementary analogies (CompA)	
Object	Electric circuit system	Simple water circulation	Obstacle race	Complex water circulation
	Current	A situation of water flow	A situation of moving players	A situation of water flow
	Wire	Large water pipe	Track	Water pipe
	Battery	Water pump	Flag raising stage	Water pump with water tower
	Bulb	Small water pipe	Single-plank bridge	Watermill
Attribute	Brightness of bulb	[a]	[a]	Rotational speed of water mill
	Voltage	[a]	[a]	Water pump pushes water up to generate power
	Strength of current	[a]	[a]	Speed of water flow
Relation	Battery connects to the wire	The water pump connects to the large pipe	The flag raising stage connects to the track	The water pump system connects to the water pipe
	Wire connects to the bulb	The large pipe connects to the small pipe	The track connects to the single-plank bridge	The water pump system connects to the water pipe
High level relation	Open circuit of the parallel/series) connection: The current can still/ cannot flow	Obstructed parallel/series pipes: The current can still / cannot flow	Broken parallel bridges: Players can still/cannot pass through it	[a]
	Parallel/series connection of the batteries: No change/increases the voltage, no change/ increases the current, and no change/increases the brightness of the bulb	[a]	[a]	Parallel connection of the water pumps/ increase the suction of watermill: No change/ increase the gap of water potential level, no change/increase the current, and no change/ increase the rotational speed of water wheel
	Parallel/series connection of the bulbs: No change/ decreases the current, decreases the brightness	[a]	[a]	Two watermills connected to the different/same pipe: Decrease the current, no change/decrease the rotational speed of watermill

Revised from Chiu and Lin (2005) as simplified version

Note: [a]Indicates analogical concepts not shown in reading materials

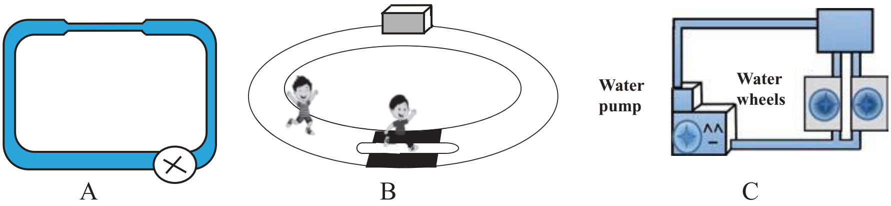


Fig. 4.1 Three types of analogical representations used in this study (Revised from Lin and Chiu 2005)

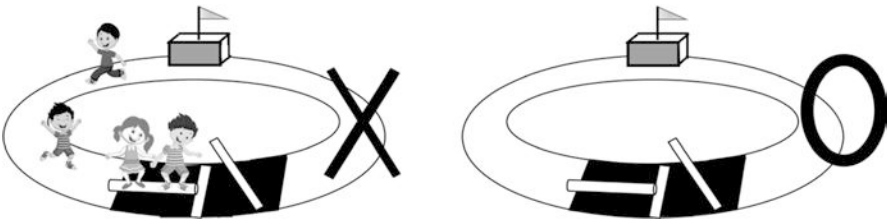


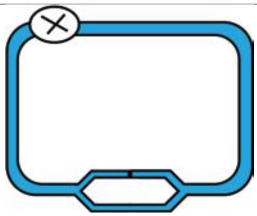
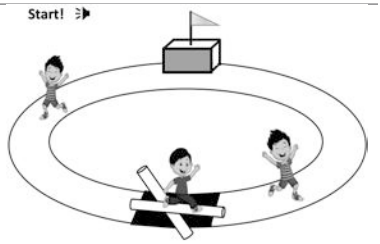
Fig. 4.2 Representations prompting possible limitations of analogies (Revised from Lin and Chiu 2005)

The representational method of one concept is explained below to serve as an example (see Table 4.3).

As far as complementary analogies learning materials were concerned, because two analogies represent two different *perspectives*—the circuit and energy in the domain of electricity—and convey different points of view (*specificity*), we mainly considered whether the selected analogical representation clearly represented drastically different *perspectives*, without requiring additional transformation or scaffolding. First, we thought that similar analogies might cause students confusion, so we chose the obstacle race over the simple water circulation to convey the concept of a circuit. Moreover, the clear, drastically different pictorial representations in the obstacle race analogy and the complex water circulation analogy indicated no need for transformation between these two analogies.

The arrangement of analogy and multiple analogies led to the following facts: no common analogy existed among the three analogical groups, the three groups could not be compared together, and comparison could only be made between a single analogy and similar analogies and between similar analogies and complementary analogies. In addition, a complex water circulation is something unfamiliar to fourth graders. So before teaching, specially designed learning materials with a complex water circulation were used to enforce students' understanding of the source domain (**Principle 1**). Moreover, tabular forms (*modality*) of the source domain and the target domain were used to make the correspondence among domains obvious (see Fig. 4.3). Therefore, we did not use scaffolding for transformation between the two analogies, but instead, we paid special attention to the transformation between the target domain and the analogical domain.

Table 4.3 Similar presentations with MAs

Explanation	Similar presentations with multiple analogies	
Text	If two bulbs are not connected in the same pathway, when one bulb is taken away, the electric current will still form in an alternative pathway, causing the other bulb to light up.	
"Arial" is used to set off two paragraphs of analogical explanation words, and parallel sentence structures are used in these two paragraphs.	This resembles the water circulation in Figure 8 (below). When one pipe is clogged, water will still go through an alternative pipe to reach the motor, forming a water circulation.	
	This also resembles the obstacle race in Figure 9 (below). When one single-plank bridge is broken, players can still pass through an alternative bridge to reach the destination, completing the race.	
Two analogical figures are used side by side, and they contain corresponding components.	 Figure 8 One pipe is clogged	 Figure 9 One single-plank bridge is broken

Revised from Lin and Chiu (2005)

Reading Materials Moreover, the reading materials for the analogical groups (i.e., experimental groups) contained not only explanation words unrelated to analogies that were originally there, but also analogical representations. To provide equal opportunities for learning, we required students in all groups to read the same number of explanation words, which for example, was composed of one paragraph of non-analogical, original explanation words and two paragraphs of analogical explanation words (see Table 4.3). More specifically, we required students in the control group to read the paragraph of non-analogical, original explanation words three times, so as to make sure they read the same number of explanation words, compared to students in the experimental groups.

4.5.3 Instruments

To understand students' perceptions of analogical limitation, personal preferences, and cognitive load for types of multiple analogical representations, this study developed three forms of 5-point Likert scale followed by interview outlines for SigA, SimA, and CompA students, respectively. The content of the Likert scale included whether each type of analogy helped students understand the electricity domain and

This relationship resembles the water circulation shown below:

Bulb	is like	→ Water wheel
Brightness of bulb		→ Rotational speed of water wheel
Battery		→ Water pump with water tower
Electric power provided by battery		→ Water pump pushes water up to generate power
Electric current		→ A situation of water flow
Strength of current		→ Speed of water flow
Wire		→ Pipe

Two water wheels connected in series increase resistance force, and thus slow down the speed of water flow, as well as the rotational speed of water wheels.

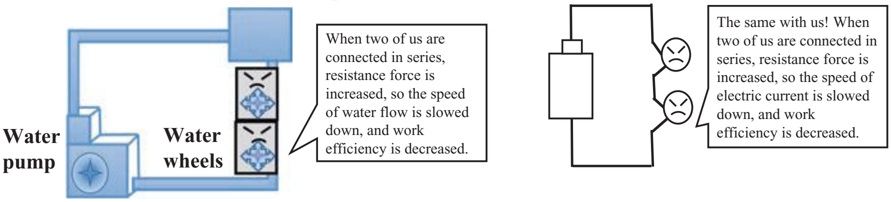


Fig. 4.3 Example of complementary analogies learning materials (Revised from Lin and Chiu 2005)

whether they liked the design of the analogical material. In addition, for the groups of multiple analogies (i.e., SimA and CompA groups), we designed items for them to self-evaluate whether they increased their sensitivity for detecting the analogical limitations and whether they increased the cognitive load when learning the material of multiple analogies. These instruments were examined by three professors of physics, two junior high school science teachers, and two experienced elementary school science teachers to establish content validity. Students were asked to report their degree of agreement with the analogical limitations, their personal preferences, and their cognitive load regarding the types of multiple analogical representations on a 5-point Likert scale. Then, students were asked to provide a rationale or examples for their rating. The interview time was 10–15 min for each student. All protocols were audiotaped.

4.5.4 Data Analysis

At first, students' Likert-scale responses for useful in detecting analogical limitation, personal preference, and cognitive load were summarized. And then, students' reasons for, and examples of, their quantitative agreements were transcribed verbatim, and their qualitative protocols were categorized by using an inductive method.

4.6 Results

Our previous studies (Chiu and Lin 2005; Lin and Chiu 2005) show that the designed learning materials with multiple analogies helped students with their conceptual change related to electricity and moderated possible cognitive load. The following results show students' self-reports of their perceptions of analogical limitations, personal preferences, and cognitive load.

4.6.1 Students' Perceptions of Analogical Limitations

The aim for complementary analogies in this study was overcoming alternative conceptions, while for similar analogies, the aim was forming schema. However, did these multiple analogies achieve the goals we set for students' perceptions? Figure 4.4 shows that all of the students agreed that the designed multiple analogies helped them be aware of the differences between the analogical domain and the target domain.

From the interviews on students' perceptions of the analogical limitations, we found that the multiple analogies helped students perceive the negative dimension of the single analogy and that students were less likely to misrecognize analogies as targets. However, the analogical limitations did not fully emerge from the interviews. For example,

(SigA, #423) water is drinkable and electricity is not drinkable.
(SigA, #913) water can be frozen and electricity cannot be frozen. …

Fig. 4.4 Numbers of students giving the rating to "whether multiple analogies were useful in detecting analogical limitations

(SimA, #710) if a player run to the middle of the single-plank bridge, it is broken and there is no other way to go …, and if the water falls that is leaking out (simple water circulation analogy), then, if it is human, then it will not continue running (the obstacle race analogy).

(CompA, #525) …oh! Current is like that (referring to be more like a complex water circulation analogy). It does not flow faster in one section and smaller [slower] in another. However, the players started to run fast and gradually slow down on the single-plank bridge (the obstacle race analogy).

From the above mentioned cases, we see that because the SigA group did not have another analogy to compare with, the analogical limitations they proposed had poor quality and mainly focused on daily attributions rather than comparison between electricity and the analogical domains. In contrast, the students in the multiple analogies group (the SimA and the CompA groups) discovered inner structures of scientific concepts through comparing analogies and were less likely to have alternative conceptions.

4.6.2 Students' Perceptions of Cognitive Load of Multiple Analogies

Students' perceptions of cognitive load were different in the SimA and CompA groups (see Fig. 4.5). All students in the SimA group reported that the multiple analogies did not increase their learning load. On the contrary, although five

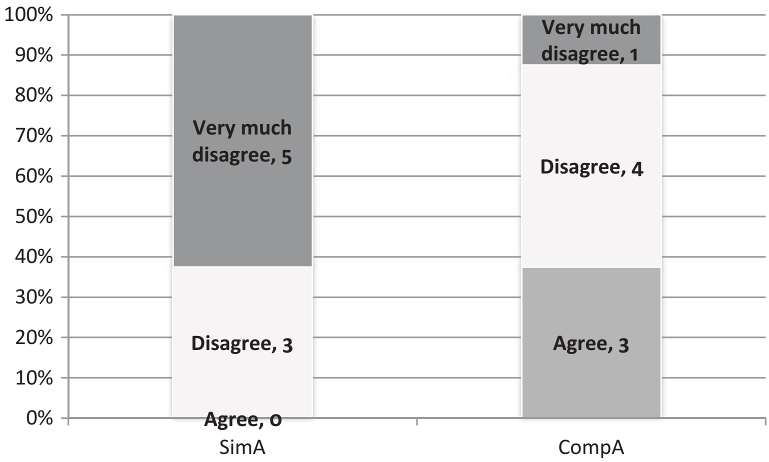


Fig. 4.5 Numbers of students giving the rating to whether multiple analogies increased their cognitive load

students in the CompA group agreed the multiple analogies did not increase their learning load, the other three remaining students held the opposite opinion. SimA group students' self-report of no increased learning load indicates that it was easy for students to learn the two multiple analogies in SimA material, which shared similar structures in the circuit perspective. On the other hand, students' in the CompA group indicated their analogies included both the energy perspective and the circuit perspective, and the former was more complex than the latter. It was reasonable for students to expend extra effort to understand the two analogies from different perspectives. Moreover, because students were not familiar with complex water circulation, and more suitable multiple analogies were not available, 20–30 min had to be allocated to help students understand the domain of complex water circulation (Chiu and Lin 2005; Lin and Chiu 2005). In other words, their cognitive load could be from the extra reading of complex water circulation. This is a limitation of this study. This point also shows the importance of students' familiarity with the analogical domain.

4.6.3 Students' Personal Preferences for Analogy

Do students personally prefer certain types of analogies? If so, what are their reasons? Table 4.4 shows that half of the SimA group liked the simple water circulation analogy, and the other half of the SimA group liked the obstacle race analogy. Two students among those who liked the simple water circulation analogy thought this analogy made them understand the circuit concept more easily. The other two students believed the water circulation analogy was more similar to the target domain than was the obstacle race analogy. In particular, one of them mentioned that the electricity flowed very fast, and the speed of the water flow was greater than students' running speed. With regards to the students who liked the obstacle race analogy, two of them enjoyed sports and running very much, so they also liked this analogy. Besides, one student thought the representation of an open circuit was like a blocked pipe. This representation was quite similar to taking out a lamp to form an

Table 4.4 The reasons why the SimA students liked the analogy

SimA	Reason	Number
Simple water circulation	It can help us understand the electricity domain. (2 students)	4
	The water system analogy is easier, simpler, higher speed (than students' running speed).	
	It is like the real electric circuit.	
Obstacle race	I like sport and running. (2 students)	4
	A broken single-plank bridge is similar to the open circuit with a broken lamp.	
	It is easier to understand.	

Table 4.5 The reasons why CompA students liked the analogy

CompA	Reason	Number
Complex water circulation	It's helpful to know the circuit connection.	4
	Students sometimes run faster or slower in an obstacle race. This situation cannot map to the electricity domain. However, the water system can map almost everything in the electricity domain.	
	The complex water circulation can tell us the speed of the water wheel, the brightness of the bulbs, and the concept of the circuit, but the obstacle race only tell us the concept of circuit.	
	It is closer to the real situation.	
Obstacle race	Using students to analogize electric current can help us understanding the flow of electric current. It is easy to memorize.	4
	It is more interesting and vivid.	
	It is easier to understand.	
	It is closer to the electric current we talked about.	

open circuit. Therefore, the student thought the single-plank bridge in the obstacle race was a better representation than the simple water circuit.

For the complementary analogies, half of the CompA students liked the complex water circulation analogy, and the other half of the CompA students liked the obstacle race analogy. The students who liked the complex water circulation analogy thought this was more similar to the target domain than the obstacle race analogy; while the students who liked the obstacle race analogy thought it was simple, vivid, and easy to understand. It is worth noting that one of the students detected the complex water circulation analogy could also represent the concept of an electric circuit, so the student thought the complex water circulation analogy was better (Table 4.5).

In summary, no matter whether students were in the CompA or SimA groups, the students who liked the obstacle race seemed to focus more on the affection aspect or the surface similarity of the analogy. Does such preference influence students' science learning? In addition, two of the SimA students liked the obstacle race analogy due to their love of sports, and they were both male. Does gender and personal interests influence students' analogy selection and then influence their science learning? All of these factors might be important in influencing the design of analogy and multiple analogies and should be considered in future research.

4.7 Conclusions and Implications

The aim of this study was to evaluate the designed multiple analogical representations that followed our proposed principle of multiple analogies (EAT) from students' perceptions of analogical limitations, cognitive load, and personal preferences. In sum, we found that the designed multiple analogies (SimA and CompA groups) facilitated students being aware of the differences between the analogical domain and the target domain, helped them discover inner structures of scientific concepts, and left them less likely to have alternative conceptions. In addition, most students agreed that the designed multiple analogies did not increase their cognitive load, but the extra reading for the CompA group students to understand the concept of complex water circulation made them spend more time and effort on learning. Finally, some students preferred the analogy of simple or complex water circulation for these analogies aided students' conceptual learning while some students preferred the analogy of obstacle race because of their love of sports. However, due to the limitation of small sample size of this current study, we cannot make explicit links between students' characteristics (such as learning experiences, resources, processing skills and domain knowledge) and their analogical preference in the multiple analogical context. For the same reason, we cannot make strong conclusion only from the perspective of students' analogical perception. It is no doubt that increasing sample size or using multiple data for triangulation is helpful to improve the quality and reliability of the research. However, after integrating results from a series of our previous studies on multiple analogies (e.g. Chiu and Lin 2005; Lin and Chiu 2005) and this study, we would be able to conclude that well-designed analogies could play important and meaningful roles in knowledge construction in learning sciences. The implications of the use of multiple analogies for science education research and practice are provided below.

4.7.1 Implications for Instruction and Learning

This study found that some students preferred the analogies that were personally familiar to them and easier (obstacle race analogy) to understand compared to analogies that were commonly used in formal instruction (e.g., simple water circulation analogy). The gap between students' prior knowledge and new scientific concepts is normally bigger than teachers expect. The use of appropriate learning tools, such as multiple analogies, can begin to bridge this gap as evident in the research. However, teachers who use multiple analogies to teach complex science concepts commonly have no prior preparation in working with and developing analogies. Research has indicated that without careful design of the analogical material, multiple analogies might lead to alternative conceptions, frustrate further science learning, and even add extra cognitive load while learning topics in science. In this study, our design principles (EAT) provided a strategy for developing multiple analogies for maximum science learning. In particular, these principles suggest detailed guidelines for teachers to examine and prepare their development of multiple analogies and help them consider the purpose for using analogies.

4.7.2 Implications for Textbooks

Although we did not investigate the impact of representations in textbooks, we noticed that most textbooks did not use multiple representations of analogies to deliver scientific concepts that were difficult to conceptualize. Based on our discoveries in this study, we would encourage textbook writers to use multiple analogies to scaffold students' learning of complex scientific concepts and use the EAT design principles to design multiple analogies. In particular, we encourage textbook writers to pay more attention to the preparations stage to examine students' cognitive ability, their prior knowledge, and their familiarity with and perceptions of analogies. These preparations would help us to align the *perspective, specificity, precision, modality*, and *complexity* of each analogical representation to students' cognitive abilities and perceptions and would make for a better transfer between different analogical representations.

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Part II
Multiple Representations: Focus On Different Approaches and Conditions

Hans E. Fischer

This Part addresses different approaches for applying specific physics multiple representations on different levels of the education system and in different physics topics. Due to the limited number of evidence-based studies on Multiple Representations in Physics Education until now, the studies reported in this Part first describe aspects of the research field in order to develop more detailed research questions and approaches. Indeed, the situation for future research is fruitful because the theoretical basis for detailed investigations can be adapted from psychology and other subjects, especially multiple representations in biology and chemistry.

In Chap. 5 by Airey and Linder, the multiple representations in physics (MRPs) are derived from a social semiotic approach for teaching and learning the refraction of light at university. A Social Semiotics approach allows the reader to examine communication and related learning processes from a more general perspective.

Chapter 6 by Kuo, Won, Zadnik, Siddiqui and Treagust also addresses students at university and geometrical optics as content, which is, quasi by definition, a prototype for visual representations in physics. This study described how students during the first four semesters develop their optics concepts and their attitudes towards related multiple representations in physics (MRPs).

In Chap. 7 by Hubber and Tytler, in-service teachers are guided to describe a representation construction approach to support their students during inquiry-based learning that includes communication and negotiation. It is pointed out that MRPs need classroom discourse and explicit teaching of their meaning and function to understand the physics concepts.

A more specific use of MRPs is presented in Chap. 8 by Nieminen, Savinaianen and Viiri focusing on the concept of force and the Force Concept Inventory. The FCI was used to test students' ability to interpret MRPs in order to evaluate the effect of using interaction diagrams to understand Newton's third law. It is shown that inter-

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action diagrams can be used in classroom situations to develop difficult concepts like all forces are interactions between different bodies.

An analysis of textbooks and electric current related MRPs are addressed in Chap. 9 by Wong and Chu. Using the approach of Educational Reconstruction, textbooks were analysed to make a connection between elementary conceptual elements and an adequate reconstruction of complex physical subjects. MRPs are seen as transmission between different levels of planning and performing lessons.

More generally, Part II shows that MRPs are an inherent part of physics. (1) They represent different levels of abstraction, like mathematics and phenomena, (2) they can be seen as mediator between different levels of abstraction like in geometrical optics between phenomena (pictures of lenses) and functional rules of constructing and predicting effects, (3) MRPs and their interpretation have to be adapted to the level of each addressee, (4) they should be taught explicitly, because physics content is always represented in many different ways dependent on both the logic of the content and the instruction, and (5) MRPs are strongly connected with learning progressions of physical meaning and can be taken as prototypes for the development of physical concepts.

Each of the five points above is relevant for teaching physics at all levels of the education system and therefore should be explicitly considered in teaching physics for future physics teachers and physicists as well.

Chapter 5
Social Semiotics in University Physics Education

John Airey and Cedric Linder

5.1 Introduction

In this chapter we discuss the application of social semiotics (Halliday 1978; van Leeuwen 2005) in the teaching and learning of university physics. For our purposes we define social semiotics as *the study of the development and reproduction of specialized systems of meaning making in particular sections of society*. In our work we have used social semiotics as a lens to understand teaching and learning in undergraduate physics. There are many similarities between our social semiotic approach and the other representational work presented in the chapters of this volume. The fundamental aim of this chapter is to introduce the supplementary and complementary aspects that a social semiotic perspective offers physics education and research in the area. Thus, in what follows, we describe our motivations for adopting a social semiotic approach and map out the similarities and differences to the extant body of work on multiple representations in physics education research. We then present a number of theoretical constructs that we have developed in our research group, and discuss their usefulness for understanding the processes of teaching and learning in undergraduate physics.

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5.2 What Is Social Semiotics?

We interpret social semiotics as a broad construct where all communication in a particular social group is viewed as being realized through the use of *semiotic resources*. In social semiotics the particular meanings assigned to these semiotic resources are negotiated within the social group itself and they have often developed over an extended period of time. The group that we are interested in consists of those involved in the discipline of physics in some way. Here, examples of commonly used semiotic resources are: graphs, diagrams, sketches, figures, mathematics, specialist language, etc. In the field of physics education research (PER) it is usual to refer to such semiotic resources as *representations*.[1]

5.3 Representations in University Physics

In the PER community a great deal of research has been carried out into the role of individual representations in the teaching and learning of undergraduate physics. See for example work on: mathematics (Domert et al. 2007; Sherin 2001; Tuminaro 2004), graphs (Christensen and Thompson 2012), language(s) (Airey 2012; Airey and Linder 2006; Brookes and Etkina 2007), diagrams (Rosengrant et al. 2009), video simulations (Eriksson et al. 2014b), gesture (Scherr 2008). Much of this work focuses on how students can achieve *representational competence* (e.g. Kohl and Finkelstein 2005; Linder et al. 2014). Commenting on the wide range of disciplinary representations available in physics, McDermott (1990) points out that these different representations are potentially educationally critical because they are able to emphasize different aspects of physics knowledge. Building on this idea, work situated at the university level has been done on the different roles that different physics representations play; investigating how they can work together to make physics learning possible (e.g. Dufresne et al. 1997; Meltzer 2005). In perhaps the most seminal work on the coordination of multiple representations in undergraduate physics, van Heuvelen (1991) suggested that in order to learn to think like physicists, students should be taught to approach problem-solving using multiple representations in a manner similar to the way trained physicists approach problems. The extension of this work resulted in a completely revised way of teaching introductory physics—outlined in the highly successful *Physics Active Learning Guide* (van Heuvelen and Etkina 2006) and the associated *Investigative Science Learning Environment* (see Etkina et al. 2014). Much of the work of our research group has dealt with the analysis of similar multi-representational approaches to the teaching and learning of undergraduate physics using our social semiotic perspective as a

[1] In the broader contexts of cognitive psychology and science education these semiotic resources are often termed *external* representations in order to differentiate them from *internal* representations.

new point of departure. For example, in our analysis of group problem solving, we have described a division of labour between physics representations, where, what is characterized as persistent representations (such as diagrams, graphs and mathematics), function as a hub around which other non-persistent representations (such as speech and gesture) can be coordinated (Fredlund et al. 2012). In the following sections we discuss how we see the similarities and differences between the representational and social semiotic approaches.

5.4 How Does Social Semiotics Differ from the Representational Approach?

At the macro-level, a case can be made for there being very little difference between our social semiotic approach to the teaching and learning of university physics and the external representational approach presented in other chapters of this book. By this we mean that our work typically deals with the ways in which graphs, diagrams, mathematics, language, etc. are best used to make physics learning possible (see for example Fredlund et al. 2015a). However, at the fine-grained level, we argue that there are three critical differences between our social semiotic approach and the approaches that are generally being presented both in this book and in the wider related literature to-date. To bring out the significance that we see here for the given field of work we discuss each of these differences under their own sub-headings.

5.4.1 Social Semiotics Focuses Primarily on Group Meaning Making

Much of the representational work carried out in the educational arena takes aspects of cognitive psychology as its starting point. Here, a common approach is to leverage dual-processing theory (Clark and Paivio 1991; Paivio 1986) together with cognitive load theory (see for example Chandler and Sweller 1991; Paas and Sweller 2012) in order to create more efficient learning environments. Cognitive load theory posits that human processing ability is extremely limited (Miller 1956). However, dual-processing theory posits that the human brain has separate processing systems for visual and verbal input that may be used simultaneously. This notion has been noted by Mayer (1997, 2003) who proposed a multimedia effect—that is, students learn more deeply from words and pictures than from words alone. Thus, given the limited processing capacity of the brain and the possibility of leveraging dual processing channels, a common focus for such research programmes is a 'snap-shot' interest in the most efficient method for communicating a certain 'message' by reducing cognitive load and simultaneously combining auditory and visual input (see Airey, p. 30). In contrast, our work takes as its starting point the ways in which professional physicists make and share meaning using semiotic resources. From this point of departure, we have focused our group's research efforts on understanding how physics teachers use disciplinary-specific semiotic resources in their teaching and how students come to use these disciplinary-specific semiotic resources in a legitimate manner (see for example Airey and Linder 2009; Linder et al. 2014; Fredlund et al. 2012, 2014, 2015a); Eriksson et al. 2014a; Airey 2009, 2011, 2012, 2014). When students learn to use disciplinary-specific semiotic resources, this process is rarely something that occurs in a single learning sequence, but rather tends to be the result of repeated exposure and use—what Kuhn (1962/2012) has likened to "finger exercises" for learning to play the piano. For us then, short-term communicative efficiency and learning over an extended period of time are equally important educational factors in the teaching and learning of undergraduate physics (see discussion of time factors and grain size in multimodal research in Tang et al. 2014).

5.4.2 Social Semiotics Includes All Forms of Meaning Making

Next, there are a number of disciplinary-specific semiotic resources used in physics that tend ***not*** to be classified as representations, but that nevertheless do have the potential to convey and share important disciplinary meanings. Here we are primarily thinking of resources such as laboratory apparatus and experimental routines. Clearly, in certain situations, such aspects can play a central role in the teaching and learning of physics.[2] However, such resources present a challenge when it comes to classifying them under the heading of external representations. Thus, we argue that the construct of representations as it is presently used in science education can be unintentionally limiting, since for many working in the field, the term explicitly excludes potentially important aspects such as physical objects and actions. In our social semiotic approach we are interested in ***all*** resources that are used for meaning making by a particular group, including both physical objects (e.g., physics apparatus) and actions (e.g., how to appropriately take measurements in a particular physics setting). Consequently, when using semiotic resources as the unit of analysis we are not asking the question; *What is this a representation of?* but rather; *What meaning can this resource convey and how is that meaning constructed by students?* This is a subtle but important difference. Thus, the term semiotic resource not only encompasses everything that is often termed external representations[3] but it also includes any other channels of meaning making that may be involved in the making and sharing of disciplinary knowledge for a particular physics situation.

[2] See for example Hammer (2000).

[3] See for example Ainsworth (2006).

5.4.3 Semiotic Resources Have a Range of Meaning Potentials

The third difference between the representational and social semiotic approaches concerns the disciplinary knowledge that a given semiotic resource is intended to convey. Meaning is seldom fixed and unequivocal—even in physics—and thus it is not uncommon for the same semiotic resource to be used for quite different purposes depending on the situation. For example, consider the use of the right-hand rule to relate current to magnetic field in electromagnetism. The exact same semiotic resource (a specific gesture) is also used describe the relationship between angular momentum and direction of rotation in mechanics. Here we can see that the application of what is essentially a generalized cross-product rule derives its particular meaning from the context in which it is used.

This problem is explicitly dealt with in social semiotics, where, by definition, all semiotic resources have a *range of meaning potentials* (Airey 2014). This idea that individual semiotic resources may have multiple disciplinary meanings is analogous to the thinking that has emerged in contemporary linguistics, where grammar is no longer viewed as a rigid system of rules, but rather as a flexible resource for meaning making (Halliday 1978). Discussing this attribute, van Leeuwen (2005), p. 1) explains his preference for the term semiotic resource: "[…] it avoids the impression that what a [representation] stands for is somehow pre-given, and not affected by its use". In this chapter we would like to suggest that this "multiple meaning" characteristic of representations deserves more attention in both the science education and PER communities. Central to our social semiotic approach, then, is that disciplinary-specific semiotic resources do not have a single, fixed meaning, but rather that each semiotic resource has been assigned a particular set of disciplinary-specific *meaning potentials*, many of which cannot be transducted into other semiotic resources.

Clearly, this notion has profound consequences for education. If semiotic resources have a range of disciplinary meaning potentials it becomes important for students to understand *which* particular aspect or aspects of the disciplinary meaning potential of a semiotic resource need to be drawn upon for appropriate knowledge construction in a given physics situation. Using such a perspective, learning can be seen in terms of coming to appropriately interpret and use the disciplinary-specific meaning potential of semiotic resources. We have termed this disciplinary meaning potential the *disciplinary affordance* of the semiotic resource (Airey et al. 2014; Fredlund et al. 2012). Disciplinary affordance is thus "*the agreed meaning making functions that a semiotic resource fulfils for the disciplinary community"*(Airey 2015). Disciplinary affordance is the fundamental theoretical construct that we present in this chapter. The other supplementary and complementary constructs that we describe in this chapter are *critical constellations, fluency, discourse imitation, pedagogical affordance, disciplinary relevant aspects* and *variation.* We argue that these constructs are useful for physics education research, regardless of whether or not one chooses to adopt our social semiotic framework. In what follows we present these theoretical constructs and discuss their usefulness.

5.5 Critical Constellations

As a disciplinary community, physics uses a wide range of semiotic resources to create disciplinary meaning. Thus physics meaning is usually realized through the coordination of combinations of semiotic resources with different disciplinary affordances:

> Think of all the words, symbols, deeds, objects, clothes and tools you need to coordinate in the right way at the right time and place to "pull off" (or recognise someone as) being a cutting edge particle physicist… (Gee 2005, p. 27)

This observation brings us to our first theoretical contribution to the field—the notion of *critical constellations of semiotic resources*. Building on the work of Airey and Linder (2009), Airey (2009) suggested that there is a *critical constellation of disciplinary semiotic resources* that is necessary for an appropriate experience of disciplinary knowledge.

This relationship is illustrated for a physics concept in a highly simplified and idealized manner in the Figs. 5.1, 5.2, 5.3, 5.4 and 5.5 (adapted from Airey 2009). In Fig. 5.1, a simple, hypothetical physics concept is shown to have six separate and

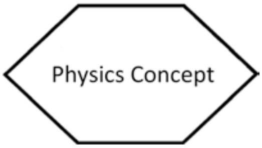


Fig. 5.1 Disciplinary concepts have multiple aspects. Here we see an *idealized* hypothetical representation of a physics concept using a *hexagon*. Each side of the hexagon represents one distinct aspect of the physics concept

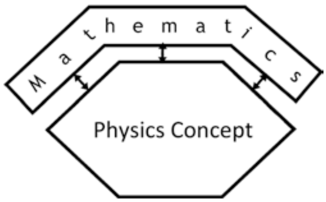


Fig. 5.2 In this case, using a mathematical resource affords access to three aspects of the physics concept

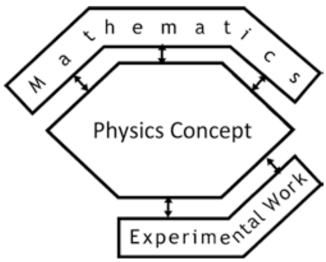


Fig. 5.3 Experimental work affords access to two further aspects of the physics concept

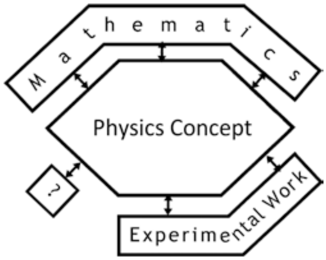


Fig. 5.4 Complete constitution of the physics concept is still impossible for students without access to the sixth aspect. Here the semiotic resource that gives access to this final aspect is marked with a question mark

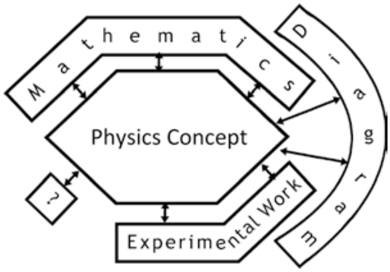


Fig. 5.5 The introduction of a diagram fails to represent the missing aspect (question mark) but does provide a transductive link between the mathematical and experimental resources

distinct aspects. For the illustrative example these aspects are represented by the six sides of a hexagon. The figures show how, while it may be possible to represent three of these aspects using mathematics (Fig. 5.2), two further aspects may require representation through experiment (Fig. 5.3).

In the illustration, the sixth, and final aspect needed for a complete constitution of the disciplinary concept is only available through a semiotic resource other than mathematics or experimental work. Figure 5.4 uses a question mark to denote this semiotic resource in order to reflect the present situation in university physics where we actually know very little pedagogically about the constellation of semiotic resources needed for appropriate constitution of disciplinary concepts. In Fig. 5.5, the addition of a diagram fails to represent this missing aspect, but does provide a transductive link between the mathematical and experimental resources.

In this final figure, a visual semiotic resource is added in the form of a diagram. In this particular illustrative case, the addition of the diagram provides a link (transduction) between the mathematical and the experimental resources, but complete constitution of the physics concept is still impossible.

5.5.1 Disciplinary Shorthand

From an educational perspective, then, it is important to note that there is a critical constellation of semiotic resources that is necessary for students to appropriately experience physics knowledge (Airey 2009; Fredlund et al. 2015a). However, this critical constellation will almost certainly never occur spontaneously whilst learning, or even doing physics. This is because both teachers and physicists only use a smaller subset of the critical constellation in their day-to-day work.[4] In fact, in many situations only a single semiotic resource is used—an equation or a diagram say—which functions as a *disciplinary shorthand* to activate a whole concept. For example, one of the reasons that Maxwell's equations are highly thought of in electromagnetism is that they represent a great deal of physics in a very compact manner. This is why it is difficult to learn physics by simply doing physics—this disciplinary shorthand needs to first be explained longhand before it can be understood (This notion is central to the concepts of discourse imitation and unpacking that we will discuss later). Clearly, a necessary condition for a critical constellation of semiotic resources to make sense to students is that they are able to appropriately interpret each of the individual semiotic resources that make up the constellation and appropriately coordinate them for the task at hand Airey 2009; Fredlund et al. 2012, 2015a) This brings us to our next construct: fluency.

5.6 Fluency

In our social semiotic model, physics is an activity that calls for leveraging the disciplinary affordances of a multiplicity of semiotic resources. Together, these resources constitute the disciplinary discourse of physics (see detailed discussion in Airey and Linder 2009). In the PER literature, mastering this disciplinary discourse is increasingly being characterized in terms of achieving representational competence (see for example Kohl and Finkelstein 2005; Linder et al. 2014). However, as we have already discussed, the term representation can be unintentionally limiting. Having adopted a social semiotic perspective, we found that we needed a term that better captured the fine-grained aspects of mastery. To do this we have used the linguistic metaphor of *fluency*[5] to characterize this mastering of disciplinary-specific semiotic resources. In our social semiotic characterization, if a person is said to be fluent in a particular semiotic resource, then they have come to understand the particular way(s) that the discipline uses that resource to share and work with physics knowledge in a given situation.

Our use of the term fluency can perhaps best be illustrated by considering the case of spoken language. In this case it is clear that in order to share meaning using this semiotic resource one first needs to attain some degree of fluency in the language in question. In our work we have argued that the same holds for all the other semiotic resources that we use in physics and that like fluency in a language, the development of fluency in these other semiotic resources entails an extended process of familiarization and use. Here we have shown how fluency in a range of

[4] For example, see the discussion later for Figure 15 where a particular task calls for a subset of disciplinary relevant aspects.

[5] Another complementary linguistic metaphor we have used to characterise representational competence is *disciplinary literacy*. See for example Airey (2011, 2013) and Linder et al. (2014).

disciplinary-specific semiotic resources begins with a process of repetition, with students using these semiotic resources to solve numerous physics problems over an extended period of time (Airey and Linder 2009). This stage is then followed by an educational approach that draws on Bruner's (1960) notion of the spiral curriculum that adds depth of disciplinary discernment (Eriksson et al. 2014a).

Our claim is that it is impossible to appropriately participate in disciplinary meaning making with a particular semiotic resource without first achieving some degree of fluency in its use (e.g. Airey and Linder 2009; see also Hill et al. 2014). Hence we define fluency as "[…] a process through which handling a particular [semiotic resource] with respect to a given piece of disciplinary content becomes unproblematic, almost second-nature" (Airey and Linder 2009, p. 33).

5.7 Fluency Alone Is Not Enough: Discourse Imitation

Although we argue that the concept of fluency in disciplinary-specific semiotic resources is educationally critical for understanding the ways that students learn to do physics, fluency alone cannot be a sufficient condition for achieving appropriate, disciplinary learning. In other words, our semiotic resource characterization of learning holds that there is more to achieving appropriate understandings in physics than achieving a particular set of fluencies in semiotic resources. In a less distinct sense this has been recognized before, for example diSessa observed:

> MIT undergraduates, when asked to comment about their high school physics, almost universally declared they could "solve all the problems" (and essentially all had received A's) but still felt they "really didn't understand at all what was going on". (diSessa 1993, p. 152)

In our characterization, the MIT students di Sessa was referring to had acquired excellent fluency in disciplinary semiotic resources, yet still lacked the associated physics understandings. As we will explain later, we argue that it is only when fluency in a critical constellation of semiotic resources is combined with an appreciation of the associated *disciplinary affordances* that appropriate and disciplinary meaning making becomes possible. We term the ability to use semiotic resources with limited or no associated disciplinary understanding, *discourse imitation* (Airey 2009). Below are examples of discourse imitation—instances where students are fluent in one or more semiotic resources of the disciplinary discourse of the university physics community, but where they have apparently not yet appropriately experienced the physics that this disciplinary discourse represents. In the following excerpt the student has just watched a section of an electomagnetism lecture where the lecturer has presented Maxwell's Equations:

> Interviewer: You've seen these equations before..?
> Student: Yeah I've seen them before, er… but I really don't know exactly what they mean [laughs].
> Interviewer: Can you tell me what this means to you?
> [pointing to the curl of the electric field formula $\nabla \mathrm{x} \mathbf{E} = 0$]

Student: Um, I think the **E** is er the intensity of er an electric field. And then the curl of **E**… [quietly to themselves] mmh equals zero…
Erm, I think this is, erm, a conservative vector field—and I know how to calculate it, but I don't know what it means.

(Airey and Linder 2009, p. 38)

We see this student as being fluent in the mathematical and oral semiotic resources with respect to the physics content that the discussion was situated in—Maxwell's equations for static fields.[6] However, discourse imitation can be seen in the words "conservative vector field". The student knows the expression and uses it appropriately, but the description carries little, if any, disciplinary meaning. It is clear that the student has not understood what this phrase represents. The student can calculate answers using the equation (in fact this student had been one of the more successful participants on the degree course up to that point), but it is evident that in this case the student does not have a good conceptual sense of what they are calculating. This ability to fluently use semiotic resources, but not appropriately experience the physics knowledge they represent—in this case, to be able to calculate, but not know what curl of **E** = 0 and conservative vector field actually mean—is taken up by another student with respect to a parallel course.

Student: [talking about a course on Tensors for Physics Students] I know it's an important concept in physics so now I think I've got some kind of abstract idea of what it is [laughs self-consciously] but er, er, I still haven't seen any er, almost no applications.
Interviewer: So this is like what you were saying about curl, but worse?
Student: Yeah, a lot worse! But I, I know mathematically very well what it [tensors] is, I just don't know how I can use it [to understand something].

(Airey and Linder 2009, p. 39)

In contrast to the previous student, this particular student can do more than just calculate answers, here the student claims to understand mathematically what tensors are, but the physics that this mathematical resource can represent is still not available to the student.[7]

In summary then, in order for students to appropriately experience disciplinary knowledge they need to become fluent in the use of each separate semiotic resource that makes up the critical constellation for that particular piece of knowledge. However, fluency in the critical constellation alone is not sufficient. From there we suggest that students still need to come to appreciate the disciplinary affordance of each of these resources and how they can be coordinated before they can understand the concept in an appropriate, disciplinary manner.

[6] If one considers the static case (i.e., constant with time) of Maxwell's Equations, one finds that the time derivatives of the electric field and magnetic flux density are zero and one form of Maxwell's equations becomes $\nabla \times \mathbf{E}(\bar{r}) = 0$

[7] For example: a tensor of rank two is defined as a system that has a magnitude and two directions associated with it. Thus, it has nine components. So, if one takes the inner product of a vector and a tensor of rank two, the outcome will be another vector that has both a new magnitude and a new direction.

5.8 Pedagogical Affordance

Introduced in the late 1970s, the meaning of the term affordance was initially framed around the needs of an organism in the environment[8] (Gibson 1979). The term has been debated at length, including the (in)famous disagreement between Gibson and Norman about whether affordance should refer to the inherent properties of objects or only those properties that are actually perceived by the organism itself (Norman 1988). More recently, the notion of affordance has been re-introduced into the educational arena. Wu and Puntambekar (2012) for example, adopt the term *pedagogical affordance,* to describe the use of representations in teaching scientific processes. (However on closer examination their use of the term can be seen to be identical to Gibson's generic affordance term.) Taking this idea further, Airey (2015) defines *pedagogical affordance* as *"the aptness of a semiotic resource for the teaching and learning of some particular educational content"*. This term breaks away from Gibson's use of affordance because no link to the experience of a particular individual is claimed—rather it is the link to the knowledge to be taught that is emphasized. Thus, whilst in an educational setting generic affordance describes what a given resource means for an individual student, pedagogical affordance refers to how useful a given semiotic resource tends to be for teaching and learning a specific piece of content. Clearly, this affordance exists regardless of whether an individual student actually experiences it or not. In this respect, Kress et al. (2001) suggested that different semiotic systems have different specialized affordances that can be drawn on in order to make meaning in an educational setting.

The suggestion, then, is that language, for example, is good for making certain types of meaning, diagrams for other types of meaning, mathematics for still other types of meaning, etc. The idea is not completely new, having been noted earlier in one form or another by a number of researchers, e.g. McDermott (1990), Lemke (1998).[9] Rather, it is the use of the term affordance to denote the meaning potential of a semiotic system that is important for our perspective on social semiotics that we have formulated in relation to the teaching and learning of university physics. Further nuancing this work, Fredlund et al. (2012) showed that different semiotic resources *within the same semiotic system* (in this case diagrams) can have quite different affordances for learning physics. In this article, a ray diagram and a wavefront diagram of the same situation were shown to fill quite different disciplinary functions. This suggests that when attempting to understand teaching and learning of physics, the focus of analysis should not only be on the range of semiotic systems available (graphs, diagrams, language, mathematics, etc.), but also on the individual semiotic resources themselves and their meaning potentials.

[8] See discussions in Fredlund et al. (2012) and Airey et al. (2014).

[9] The reader is also referred here to Lemke's (1999) discussion of the appropriate semiotic resources for presenting typological and topological meanings.

5.9 Disciplinary Affordance: The Meaning Potential of a Semiotic Resource

For the study of teaching and learning in higher education we have proposed the concept of *disciplinary affordance* (Fredlund et al. 2012). This term has parallels to Kuhn's (2012, p. 182) disciplinary matrix in that it "[…] *refers to the common possession of disciplinary practitioners*". Airey (2015) defines disciplinary affordance as "*the agreed meaning making functions that a semiotic resource fulfils for a particular disciplinary community"*. In line with our social semiotic approach, disciplinary affordance (like pedagogical affordance) makes a radical break with the work of both Gibson and Norman by shifting the focus from the individual to the collective. Thus, rather than referring to the discernment of a single individual (or organism), the concept of disciplinary affordance refers to the disciplinary community as a whole. Note here that although the disciplinary affordance of a semiotic resource usually tends to leverage aspects of the particular (generic) affordances of a given semiotic system (as suggested by Kress et al. 2001), this is clearly not always the case. Disciplinary meaning can also be assigned to a semiotic resource by the application of a convention (Airey et al. 2014; Fredlund et al. 2012). Moreover, the history of physics shows us that the disciplinary affordances of semiotic resources are not "set in stone" but can change subtly (or even radically) as associated knowledge about a particular phenomenon develops over time (e.g. see discussion of the historical development of the Hertzsprung-Russell diagram in Airey 2014 and the discussion of Einstein's introduction of the convention for the omission of summation signs in Fredlund et al. 2014). Clearly then, from this viewpoint the focus shifts away from Gibson and Norman's disagreement about whether the affordances of a semiotic resource are inherent or discerned. Rather, from an educational perspective the issue is whether the meaning of a semiotic resource, as experienced by an individual student "corresponds" to the disciplinary affordance that is taken to be appropriate by the disciplinary community.

In this respect we have claimed that, "The power of the term for educational work is that learning can now be framed as coming to discern[10] the disciplinary affordances of semiotic resources" (Airey et al. 2014, p. 20) (see for example the discussion of the development of the meaning of ray diagrams in Airey 2014; and the discussion of the historical development of the Hertzsprung Russell diagram in Airey and Eriksson 2014).

[10] Leveraging Bruner's (1960) notion of the spiral curriculum, we have also drawn some tentative conclusions about the ways in which students come to discern these disciplinary affordances, documenting what we term an *anatomy of disciplinary discernment* (Eriksson et al. 2014a). Here, students are seen to progress from initial, non-disciplinary discernment through four stages: disciplinary identification, disciplinary explanation, disciplinary appreciation and disciplinary evaluation.

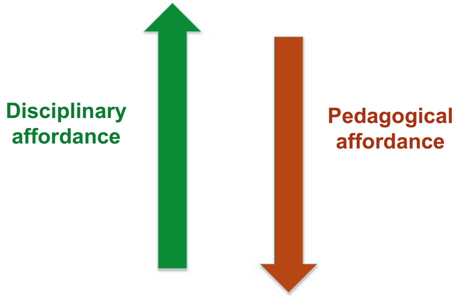


Fig. 5.6 The relationship between disciplinary affordance and pedagogical affordance
Disciplines leverage the disciplinary affordances of highly specialized semiotic resources in order to make meaning. These semiotic resources function as a type of "disciplinary shorthand". An increase in pedagogical affordance involves unpacking this disciplinary shorthand and thus will almost always result in a decrease in disciplinary affordance.

5.10 The Relationship Between Disciplinary Affordance and Pedagogical Affordance

Since we have defined disciplinary affordance as *the agreed meaning making functions that a semiotic resource fulfils for the disciplinary community* and pedagogical affordance as *the aptness of a semiotic resource for the teaching and learning of some particular educational content* it becomes possible (even usual) for the same semiotic resource to have both disciplinary and pedagogical affordances (i.e. the two do not mirror each other). Thus, Airey (2015) suggests an inverse relationship between disciplinary affordance and pedagogical affordance. That is, an increase in the pedagogical affordance of a semiotic resource will almost inevitably lead to a decrease in the disciplinary affordance of the resource (see Fig. 5.6). This is because, as explained earlier, part of disciplinary expertise draws on the creation of "disciplinary shorthand" in order to share meaning in more succinct and efficient ways. Naturally, then, any additions or modification made to this communication system in order to make it more educationally accessible will *decrease* the disciplinary affordance. At the same time the educational corollary is that the pedagogical affordance of a semiotic resource can be *increased* by *unpacking* its disciplinary affordance. (Redish et al. 2006; Fredlund et al. 2014; Fredlund 2015).

5.11 Unpacking Disciplinary Affordance

Fredlund et al. (2014) show that the disciplinary affordance of semiotic resources will inevitably need to be 'unpacked' for students to some degree. To illustrate this point they demonstrate how something so seemingly innocuous as a basic circuit diagram in the student laboratory can pose significant learning challenges. Their

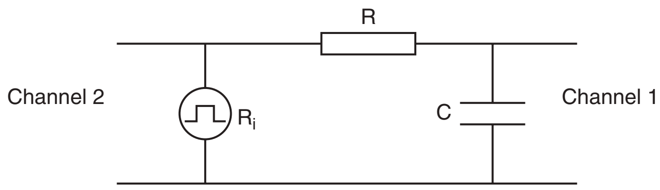


Fig. 5.7 Circuit diagram (taken from the laboratory notes)
Note: Students were asked to connect this circuit, however, the connections for signal and ground are not shown

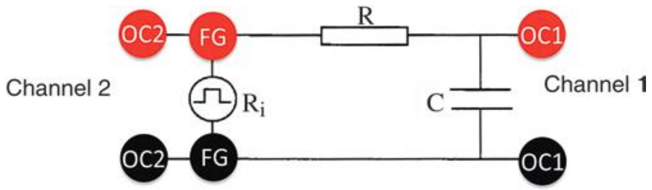


Fig. 5.8 Increasing the pedagogical affordance
The disciplinary affordance of the intended circuit unpacked by addition of *coloured dots* (*red* for signal, *black* for circuit ground). *OC* oscilloscope input channel and *FG* function generator output. This circuit shows the oscilloscope measuring both the function generator output—in this case a square wave voltage (channel 2), and the charge across the capacitor (channel 1) (Color figure online)

example circuit can be connected in eight possible ways. Although each one of these eight permutations ostensibly ‘matches’ the circuit diagram, only one is accepted by the discipline of physics as being “correct”. Thus, since there are these eight possibilities, Fredlund et al. (2014) argue that the disciplinary relevant aspects needed to correctly connect the circuit (i.e. the signal and ground connections) do not get explicitly shown in a standard circuit diagram. The authors go on to convincingly illustrate how the addition of coloured dots to indicate signal and ground can be used to unpack the disciplinary affordance of the circuit diagram—effectively making a semiotic resource of greater pedagogical affordance in that it dramatically reduces the visual ambiguity. Figure 5.7 shows the (standard) circuit diagram students were asked to connect. Figure 5.8 shows how the pedagogical affordance of the original diagram can be increased by unpacking the disciplinary affordance by using red dots to indicate the signal relative to the circuit ground and black dots to indicate circuit ground.

Figure 5.9 shows the physical connections made by students and Fig. 5.10 shows the analysis of this circuit using the new, unpacking semiotic resource. Note that in Fig. 5.10 it is possible to identify inappropriate connections, in this case short circuits, that cannot be immediately discerned using the original semiotic resource (Fig. 5.7).

The modified semiotic resource (the circuit diagram augmented with red and black dots) makes visible important disciplinary relevant aspects that were not visible in the original disciplinary semiotic resource—in our terms, the pedagogical

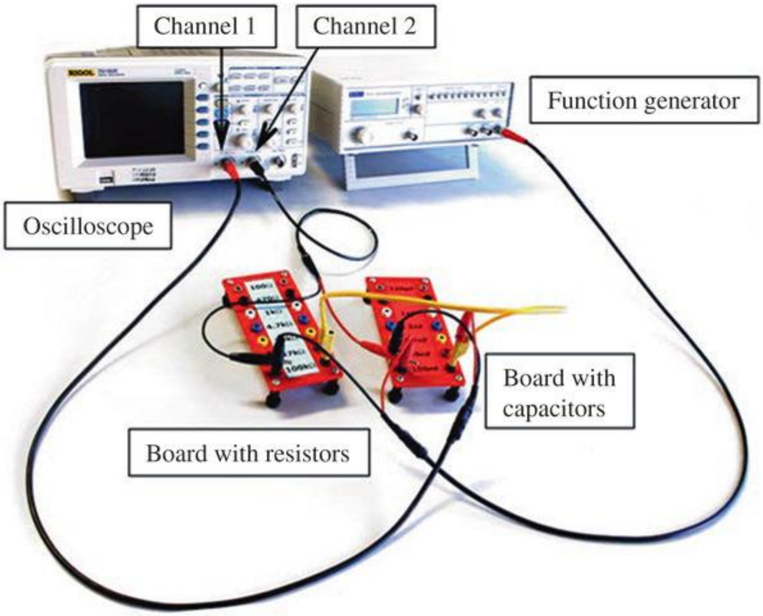


Fig. 5.9 Incorrect physical circuit made by students
The reason the circuit is incorrect cannot be seen by referring to the original diagram in Fig. 5.7

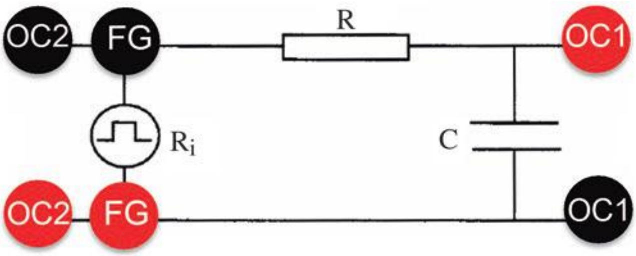


Fig. 5.10 Incorrect student circuit represented using the unpacked semiotic resource
Note: Here it is now possible to discern short-circuits in the connections. These are not visible using the diagram in Fig. 5.7

affordance of the semiotic resource has been increased. However, in making this addition, the disciplinary affordance of the resource has actually been reduced, since the power of the disciplinary shorthand has been weakened. Clearly, when two physicists communicate, drawing these additions would be both time-consuming and unnecessary. In summary then, we suggest that it is important for teachers to understand when they might need to unpack semiotic resources and how this may be achieved by modifying the semiotic resource, so that their students can discern aspects that are taken for granted in the 'packed' version of a given semiotic resource.

5.11.1 Disciplinary Relevant Aspects

The next construct we would like to discuss is that of *disciplinary relevant aspects*. In the same way that semiotic resources have a range of meaning potentials that need to be selected between, disciplinary concepts have a range of aspects associated with them: typically, for a given educational situation only a discrete set of these aspects will be relevant and/or needed. Drawing on Fredlund (2015) and Fredlund et al. (2015b, c), Fredlund et al. (2015a, p. 2) define disciplinary relevant aspects as "[…] those aspects of physics concepts that have particular relevance for carrying out a specific task". They illustrate disciplinary relevant aspects using an example of the refraction of light. For the refraction of light potential disciplinary relevant aspects would include:

Angle
Direction
Distance
Frequency of light
Medium
Position
Refractive index
Sine of angle
Speed of light
Temperature
Time
Wavelength of light
Fredlund et al. (2015a, p. 6)

As the authors point out, for any given problem relating to refraction, only a smaller subset of these aspects will be called for. For example, an acceptable, qualitative description of why refraction occurs has been shown to be dependent on just three of these aspects: the speed of light, the medium and the direction (Fredlund et al. 2012; Kryjevskaia et al. 2012).

5.12 Noticing Disciplinary Relevant Aspects: The Variation Theory of Learning

Earlier we discussed how teachers can help their students to discern disciplinary relevant aspects that are not visually present in a semiotic resource; by a process of unpacking that increases the pedagogical affordance of the resource. We will now move on to the idea of helping students to notice the disciplinary aspects that *are* already present in semiotic resources. As we pointed out in our earlier discussion our perspective depicts semiotic resources as having a range of meaning potentials. Consequently, it is important that students pay attention to the appropriate meaning potentials for the situation at hand. Students' attention can be directed by leveraging the ideas of *variation theory*. The variation theory of learning posits that

Fig. 5.11 An example of an unstructured semiotic resource
It is unclear here what aspect is to be focused on

possibilities for learning are maximized when the aspects students are expected to notice are varied against an invariant background (Marton and Booth 1997: Booth and Hultén 2003; Marton and Tsui 2004; Marton and Pang 2013; Marton 2015). Put simply, humans tend to notice that which varies. This fact can be leveraged by a teacher in an educational setting by holding everything in a particular semiotic resource constant (the background) except for a chosen aspect that students need to notice, which then becomes an essential part of the foreground. The theory has been used successfully in a wide range of disciplines, for example, mathematics (Runesson 2005), economics (Pang et al. 2006), chemistry (Lo 2012), language (Marton et al. 2010) and engineering, (Bernhard 2010). In our work we have shown how variation theory can be used to great effect in the fields of optics and electrostatics.

The photograph in Fig. 5.11 gives an everyday example of how it may be difficult for the uninitiated to know what aspect of a semiotic resource is relevant. Imagine this picture being introduced with the words “As you can plainly see…”—one simply does not know where to look or what aspect to focus on.[11]

Imagine that in Fig. 5.11 the intention was to convey that bolts can have different types of thread. Variation theory suggests that this aspect will best be discerned by comparison of two bolts that are in every way identical except for the aspect we are interested in (difference against a background of sameness). In Fig. 5.12, two bolts have been oriented in the same way, they have the same length, the same material and the same type of head. The only varying feature is the pitch of the thread on the bolts. When such a difference is set against such a background of sameness, the potential of an aspect being spontaneously noticed is optimized. We argue that

[11] Figure 5.11 also provides an interesting illustration of variation theory. Most people when they first see Fig. 5.11 tend to notice the washer since this is seen as a difference in a background of sameness.

Fig. 5.12 Variation against a background of sameness Since all other aspects of these bolts are identical, it is the difference in pitch that is noticed

the same approach can be taken to helping students to discern the appropriate disciplinary relevant aspects of semiotic resources.

How then can teachers help their students to discern the appropriate disciplinary affordances of semiotic resources? Using the variation theory of learning (Marton and Booth 1997) we have demonstrated, both theoretically and empirically in two interconnected articles (Fredlund et al. 2015a, b), how learning can be made possible through a three step process:

1. Identify the disciplinary relevant aspects for a given task
2. Select appropriate semiotic resources that showcase these disciplinary relevant aspects
3. Vary each of the aspects whilst holding everything else in the semiotic resource constant (i.e. setting up difference against a background of sameness).

5.13 An Example of Structured Variation in a Single Semiotic Resource

We will now illustrate a teaching sequence where the variation theory of learning is applied together with our work on disciplinary relevant aspects. Part of our work in this area has involved asking students to explain why refraction of light occurs. Here we found that students and teachers alike typically begin by drawing a ray diagram similar to Fig. 5.13. However, as we mentioned earlier, a qualitative explanation of why refraction occurs essentially involves three disciplinary relevant aspects: speed of light, medium and direction (Fredlund et al. 2012; Kryjevskaia et al. 2012) and all of these aspects are not directly discernable in a ray diagram.

Since speed of light is not directly discernable in a ray diagram it is impossible to give a qualitative explanation of refraction using this semiotic resource without extensive unpacking. An example of a much more appropriate resource to call on is a wavefront diagram.[12] This is because it has disciplinary affordances related to all

[12] It is, of course possible to see the wavefront diagram as an unpacked version of the ray diagram.

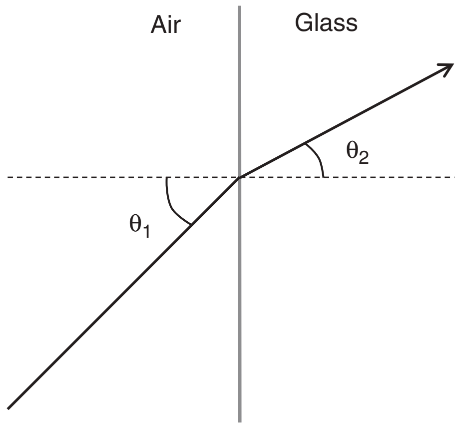


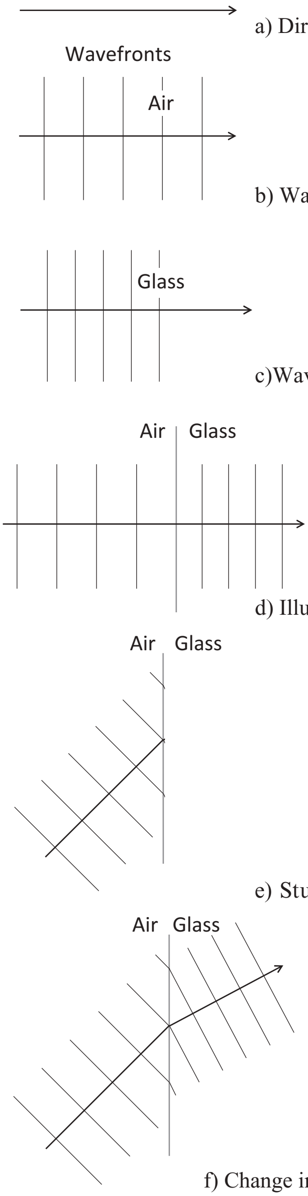
Fig. 5.13 A typical ray diagram of the refraction of light
Disciplinary relevant aspects direction, medium and angle are visible but the speed of light is not visible

three of the required disciplinary relevant aspects. In Fig. 5.14, direction is shown by an arrow, medium is denoted by labels together with a boundary line and speed is represented as proportional to the distance between wavefronts (similar to the way dots on tickertape can be used to indicate speed in mechanics experiments).

Having identified the appropriate semiotic resource, we will now illustrate how these aspects may be systematically varied to help students notice them. In the diagram (a) in Fig. 5.14, direction is shown using an arrow. Then in (b) wavefronts are drawn in for the medium of air. The separation of these wavefronts is proportional to the speed of light.

Next, in order to connect the distance between wavefronts to speed of light, students are asked to predict whether the wavefronts will be closer together or further apart in glass, leading to them generating diagram (c) with wavefronts for glass. These two diagrams can then be combined in (d) to highlight the covariation between medium and speed of light. Finally, for the case where light reaches the boundary at an angle illustrated in (e), students are asked to draw in the wavefronts (given that they need to be continuous) in order to produce the final diagram (f) in the series. Here the only way to reconcile the different distances between the wavefronts is to change the direction, thus leading to a qualitative description of the refraction of light.

Having now demonstrated a special case where appropriate disciplinary learning may be fostered by working exclusively within one semiotic system (diagram), we are now in a position to discuss the more usual position, where appropriate construction of disciplinary knowledge is contingent on discerning disciplinary relevant aspects across a number of semiotic resources.



a) Direction

b) Wavefronts in air (separation proportional to speed)

c)Wavefronts in glass (separation proportional to speed)

d) Illustrating covariation of medium and speed

e) Students are asked to draw in continuous wavefronts…

f) Change in direction generated and related to change in speed and medium

Fig. 5.14 A teaching sequence where the three disciplinary relevant aspects: speed of light, medium and direction are each varied in order to provide a qualitative description of the refraction of light

5.14 Multiple Semiotic Resources

How then, can the disciplinary affordances of *multiple* semiotic resources be leveraged for teaching and learning in physics? In order to demonstrate our ideas, first imagine a hypothetical physics concept that involves a system of seven disciplinary aspects. As we have argued earlier, access to all of these aspects can only be made possible by leveraging the disciplinary affordances of a wide range of semiotic resources. In Fig. 5.15, these aspects have been denoted by seven coloured boxes. Now suppose that the appropriate completion of a given disciplinary task requires the combination of three of these aspects—hypothetically characterized as red, orange and yellow. Clearly, the most appropriate semiotic resource for carrying out this task would be one with disciplinary affordances that combine these three aspects alone (as we used in the previous example). However, in most situations it is actually very unusual to find a single semiotic resource that has the disciplinary affordances that provide access to all the aspects required for a particular task. Rather, the disciplinary affordances of a single semiotic resource may only allow access one or two of the required aspects, necessitating the use of more than one semiotic resource (see our earlier discussion of critical constellations).

Following our earlier discussion of semiotic resources having a range of meaning potentials, there is a high probability that a semiotic resource will have other disciplinary affordances not related to a particular task. Add to this non-disciplinary

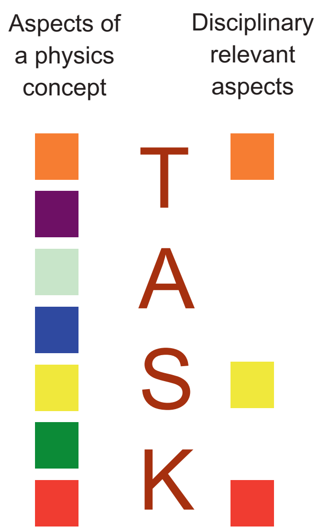


Fig. 5.15 Disciplinary relevant aspects for a given task
Illustration of the range of disciplinary aspects (*coded as colours*) that together make up a (hypothetical) physics concept, showing the disciplinary relevant aspects that the task calls for—the sub-set required for a performing a particular task (Colour figure online)

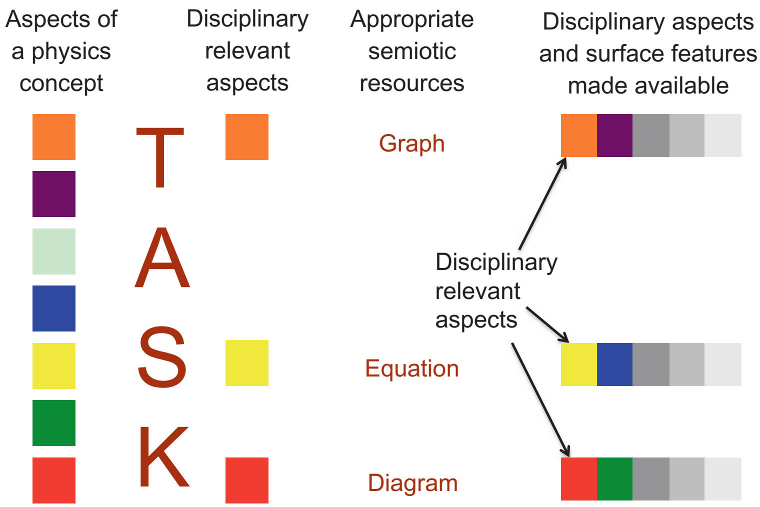


Fig. 5.16 Choosing the appropriate semiotic resources
In this case the combination of three semiotic resources (graph, equation and diagram) is needed in order to provide access to the disciplinary relevant aspects for the task. However, each of these semiotic resources also presents other disciplinary aspects that are **not** required for completion of this particular task as well as surface features—aspects of the semiotic resources that have no disciplinary meaning (denoted by the *grey boxes*) (Colour figure online).

affordances—what Podolefsky and Finkelstein (2007), p. 165) term the 'surface features' of representations—and one can see that it is not as simple as choosing the critical constellation of semiotic resources needed for the task.[13]

Successful completion of a task, then, often requires students to pay attention to disciplinary relevant aspects across more than one semiotic resource simultaneously, whilst ignoring any other disciplinary and non-disciplinary aspects (surface features) that these semiotic resources may make available.[14] In Fig. 5.16 the disciplinary relevant aspects for the task are made available by combining three semiotic resources (graph, equation and diagram). The task for a teacher, then, becomes one of encouraging and enhancing the possibility of *disciplinary discernment* (Eriksson et al. 2014a, 2014b). This entails noticing and focusing on the appropriate disciplinary aspects across a range of semiotic resources, whilst 'pushing' unrelated

[13] In this respect, Linder (1993) argues for depicting physics learning in terms of learning to contextually discern aspects in functionally appropriate ways in order to deal with tasks set in these contexts in the optimal disciplinary way. And Marton and Pang (2013, p. 31) point out how, 'Becoming an "expert" frequently amounts to being able to see particular phenomena in particular ways under widely varying circumstances'

[14] Here we are drawing on Marton & Booth's idea of 'simultaneity' (e.g. 1997, pp. 100–107) which refers to how contrasts between the 'taken-for-granted background' and an educationally critical aspect of the 'object of learning' are made explicit, so that they are simultaneously present to the learner. The idea can also be related to the concept of extraneous cognitive load (e.g. Sweller 1994).

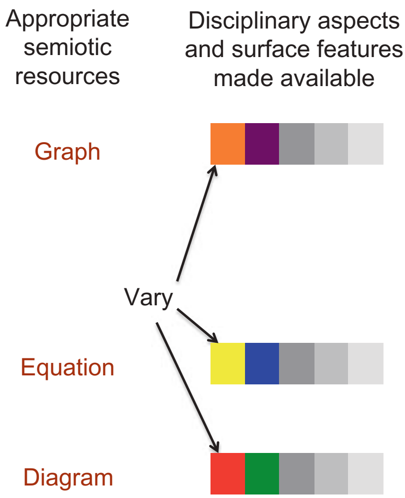


Fig. 5.17 Using variation to help students to discern the disciplinary relevant aspects
In order to facilitate discernment, each of the disciplinary relevant aspects needs to be varied whilst holding all other aspects and surface features constant

disciplinary aspects and surface features into background awareness. Using this description it is easy to appreciate the difficulties that can emerge in attempts to successfully and appropriately complete particular disciplinary tasks.

Following our earlier description of the use of variation, the disciplinary relevant aspects for the task will need to be varied whilst holding all other aspects constant. This is done in order to help students discern these aspects from the surface features and other disciplinary aspects not directly relevant for a particular disciplinary task (see Fig. 5.17).

In this case since there are three disciplinary relevant aspects, this means that for students at the introductory level, three rounds of variation are called for in order to optimize the possibility of achieving the learning objective. Holding everything else constant, the disciplinary relevant aspect in the graph could be varied and the corresponding effects in equation and diagram could then be noted. The same procedure would then need to be carried out for the disciplinary relevant aspects made available by the equation and diagram respectively.

5.15 Conclusions

In summary, we suggest that there are a number of elements of our theoretical and empirical work framed by our depiction of semiotic resources that have direct bearing on the teaching and learning of university physics with multiple representations. We believe the constructs we have presented have a relevance that reaches beyond adopting a social semiotic perspective to teaching and learning of physics. Indeed, we argue that the ideas we present provide the basis for a new way of characterizing learning that has wide applicability even within cognitive approaches to work with multiple (external) representations.

First, we have claimed that there is a *critical constellation of semiotic resources* that is needed for appropriate disciplinary knowledge construction. We argue that teachers need to contemplate which critical constellations of semiotic resources are necessary for making which parts of physics knowledge available to their students. This claim lies at the heart of developing a functionally appropriate, multi-representational approach to the teaching and learning of physics. As a corollary to this claim, we suggest that students will be unable to appropriately learn particular parts of physics before they have become *fluent* in each of the semiotic resources that form the critical constellation for those particular parts. For example, an appropriate, disciplinary understanding of Ohms law will naturally be contingent on students becoming fluent in, its mathematical formulation as well as other semiotic resources such as current-voltage graphs, circuit diagrams and hands-on work with resistors, wires, bulbs, etc. Thus, we suggest that teachers need to provide opportunities for their students to achieve fluency in the range of semiotic resources that make up the critical constellation for a given concept. For students, we have shown this is often achieved through a process of repetition, similar to the development of fluency in a foreign language.

How, then, can physics teachers decide which exercises to give their students? What kind of repetition is needed and with which resources? Here we claim that this can only occur when teachers understand the *disciplinary affordances* (the agreed meaning-making functions) of the individual semiotic resources they use in their teaching and the ways in which these can gainfully be combined to build physics knowledge.

One bi-product of a lack of student fluency in the critical constellation of semiotic resources needed for appropriate knowledge construction is *discourse imitation;* that is, students who use physics resources appropriately, but without the deeper understanding that the discipline would normally associate with this use. We have characterised discourse imitation as occurring because students initially become fluent in *only some of the semiotic resources* needed for appropriate, disciplinary knowledge construction. For this reason we suggest that teachers should expect discourse imitation from their students and should therefore pay close attention to what students say and the other semiotic resources they draw on, even when they seem to have given the "correct" answer to a question.

One further issue here relates to the physics' "obsession" with situating the more advanced levels of undergraduate physics learning almost exclusively in mathematical presentations of content and mathematical problem solving. We have previously suggested that students may be pushed towards discourse imitation if only one semiotic system (mathematics) is used for evaluating student knowledge (Airey and Linder 2009, pp. 42–43). Why should students attempt to become fluent in other disciplinary semiotic resources, if the perception is that only the mathematical semiotic resource is what is needed to become competent in the discourse of physics? Or, put another way, how can we expect students to appropriately understand physics if they are only using mathematics and ignoring the contributions of other semiotic resources?

The next issue we raise is the unpacking of the disciplinary affordance of semiotic resources in order to create resources with a greater pedagogical affordance. Here we have shown that creating new semiotic resources that 'unpack' the powerful disciplinary shorthands used in physics, provides new opportunities for effective noticing of educationally critical aspects.

Finally, we have claimed that there is a specific set of aspects that make up each disciplinary concept, and that different semiotic resources, with their different disciplinary affordances present different possibilities to represent these aspects. From this standpoint, it is clear that for the performance of any given disciplinary task there will be a smaller subset of these aspects—what we have termed the disciplinary relevant aspects that are necessary for successful completion of the task. These aspects will typically be represented by different semiotic resources and thus successful completion of any physics task will be contingent on the coordination of multiple semiotic resources.

From this positioning we have suggested a three-stage strategy for the teaching of physics where teachers need to begin by identifying the disciplinary relevant aspects. From there they select appropriate semiotic resources with disciplinary affordances that best give access to those aspects. Then, following the variation theory of learning, in order for students to notice these disciplinary affordances, each aspect needs to be varied against a constant background both within and across the multiple semiotic resources.

The account we have given here is only a brief introduction to the empirical and theoretical work that we have carried out in the field of representation in university physics. The interested reader is therefore referred to the original papers as detailed in the reference section.

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Chapter 6
Learning Optics with Multiple Representations: Not as Simple as Expected

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6.1 Teaching and Learning with Multiple Representations

Effective scientific discourse in physics involves the flexible use of multiple representations such as describing how one can see an image in a mirror and then making a sketch to show how this can happen. Also effective physics instruction comprises different representations such as describing the physical behaviour of body and demonstrating this behaviour with velocity-time or distance-time graphs. As is evident from these examples, when more than one way is used to explain an event or phenomena, the possibility of understanding what is occurring increases (Ainsworth 2008). In these contexts, multiple representations are the various ways of communicating a scientific idea, such as words in verbal or written explanations, pictures, diagrams, graphs, computer simulations, and mathematical equations (Rosengrant et al. 2007; Tsui and Treagust 2013).

Each representation has its own features and meanings and so can be used for particular scientific and educational purposes. For example, diagrams are suitable for presenting and explaining conceptual models whereas graphs make it easy to show mathematical relations between different variables (Chittleborough and Treagust 2008). Various representations are used in different instructional settings, yet these representations can be generally categorized as descriptive (involving words, graphs or tables), figurative (with pictures, analogies or metaphors), mathematical, experimental, and kinaesthetic or embodied representations (Niebert et al. 2012).

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Learning with multiple representations has been recognized as a potentially powerful way of facilitating understanding in science (Tytler et al. 2013). For some years now, educational research in abstract disciplines such as physics indicates that the integration of multiple representations can enhance students' problem solving skills (Chue and Tan 2012; Larkin and Simon 1987). Multiple representations serve to make implicit knowledge explicit, encourage students to attempt solving problems using more than one approach, and to reorganize knowledge and re-represent a problem in multiple ways, just as scientists do (Kohl and Finkelstein 2008). Multiple representations can highlight aspects of the concept for students and lead to a convergence across representations that may improve or strengthen the depth of understanding (Adadan 2013). In order to attain these benefits, many studies trialled learning with integrated representations (i.e. relevant representations presented for learners simultaneously to solve a problem) and found this leads to better performance or knowledge construction than learning with non-integrated representations (e.g., van der Meij and de Jong 2006).

Many research papers describe the advantages that multiple representations can bring to students (e.g., Ainsworth 2008; Galili 1996) but research also has shown that it is not easy for learners to gain those advantages and herein lies the challenges addressed in the research reported in this chapter. When learning with multiple representations, learners need to conduct various tasks, such as understanding the syntax and domain of each representation, and relating and translating one against the others. For example, if students do not know what a straight and dotted line represents in a ray diagram, they cannot represent their understanding with a ray diagram. Likewise, if they do not understand the ray model of optics and the advantages and limitations, they may not gain the benefit of learning with geometric ray diagrams. Once students understand the syntax and domain of each representation, they need to relate and translate multiple representations—that is, to find the corresponding features of two or more representations, and to interpret the similarities and differences between them (Hill and Sharma 2015; Nichols et al. 2013). Once students understand ray diagrams and lens equations, they need to find how they correspond to each other. This moving back and forth between representations could help learners to complete complex cognitive tasks and to acquire scientific discourse (Nichols et al. 2013).

In order to help students, overcome the difficulties and receive the benefits of using multiple representations for learning, researchers have argued that multiple representations need to be handled carefully in instruction (Ainsworth 2008) and the actual classroom teaching strategies are very important (van der Meij and de Jong 2006) to achieve successful learning with multiple representations. Students need to understand the reasons for various teaching strategies with multiple representations to gain advantage of using the different representations (Van Heuvelen and Zou 2001).

Instruction needs to involve not only those representations provided by the instructor but also student-generated representations in order to cultivate students' competence in interpreting, integrating and reproducing multiple representations (Tytler et al. 2007). If students only participate in teacher-centred activities, their opportunities for learning may be constrained (Greeno and Hall 1997). Waldrip et al. (2010) pointed out that students' representations can be a tool for judging and developing their understanding. Learners can use their representations to record their initial and new thinking and scaffold their understanding and explore science ideas (Tytler et al. 2006). As Bodemer et al. (2004) emphasized, students should be encouraged to integrate multiple representations themselves because it helps them to think, predict and make their claims. It also increases the ownership of their work, and raises students' learning motivation and creativity (Hubber 2005). Furthermore, the knowledge developed in this way is more durable than just using teacher's representations for learning (Waldrip et al. 2010).

In a university setting with a large number (hundreds) of student enrolments, however, introductory physics courses are often taught in a large lecture hall with limited opportunities for student-centred activities, such as expressing their ideas through self-generated representations and discussing their conceptual understanding. Because of this constraint, studies have identified various issues in university students' competence and their knowledge in introductory physics. The issues include: (1) students cannot reason about physical processes qualitatively but rather they know a few facts and equations which are randomly chosen for solving a problem (Van Heuvelen 1991); (2) few students attempt to understand how the major principles work or apply their knowledge to the real world when learning physics (Prosser et al. 1996); (3) most students knew that physics works from general principles when solving problems but they tend to work from special cases (Lin 1982).

6.2 Teaching and Learning Optics with Representations

Many research studies have identified students' alternative conceptions about light and its properties (Chu and Treagust 2014; Fetherstonhaugh and Treagust 1992; Shapiro 1994). Students usually hold alternative conceptions of "seeing" (perception of light) (Andersson and Kärrqvist 1983) and of images (Galili 1996; Galili et al. 2006). Indeed, optics is one of the most challenging topics in introductory physics (Mzoughi et al. 2007) because this domain cannot be understood by tactile experience or concrete frames of reference (Heywood 2005). Galili (1996) noted that students could not distinguish between *matter-based* concepts and *process-based* concepts when learning optics and this may affect students to change their alternative conceptions. To help students' conceptual change, many approaches have been implemented including different teaching models (Dedes and Ravanis 2009), teaching modules and computer programs (Blanquet et al. 1983).

Within these approaches, one key element in learning this topic is drawing ray diagrams, the use of which is considered a main representation for communication in optics (Ronen et al. (1993). However, research has shown that students do not readily accept this representation and struggle with drawing and interpreting ray diagrams (Galili 1996). In order to help students to learn optics concepts better, it is necessary to assess the students' capability in using ray diagrams and other representations and devise a better way to encourage the integration of multiple representations in their learning.

In this study, we designed an assessment instrument that prompts students to use multiple representations and investigated how students use ray diagrams and other representations on the topic of optics when answering the questions. With a focus on the dynamic interaction between the construction of deeper conceptual understanding and the use of multiple representations, we investigated the following research questions:

1. How, and to what extent do students use different representations to show their understanding of optics concepts, when prompted to do so?
2. To what extent did students perceive that the different representations help them improve their understanding of the optics concepts?

6.3 Research Methods

6.3.1 Research Design

This study adopted a case study design to investigate students' use of multiple representations in the first year physics course for non-major students over 2 years. This study is bounded by the location (non-major physics course at one university in Australia), time (for four semesters), and curriculum content (optics), without any controlled treatment. As Anderson (1998) indicated, case study designs are suitable for educational situations which do not easily allow tight control or experimental manipulation. The teaching and learning situation was an established physics program and it was not our own intervention. This study employed both quantitative and qualitative data with an exploratory pretest-posttest design (Creswell 2012). The research essentially involved qualitative data through students' responses in the pre- and post-assessments and interviews with the same students. The qualitative data from the assessment were analysed against a scoring rubric, creating quantitative data.

6.3.2 Research Procedures

To investigate the use of multiple representations in a first-year physics course, we observed the instructor's use of different representations when teaching optics. The first author observed all lectures and tutorials as a participant observer and made notes on the questions and discussions held in class. We developed and administered an assessment instrument to measure students' use of multiple representations. The instrument development went through two pilot studies with two different student cohorts in the course. Interviews were also held at the end of the semester with students to ascertain their views about the use of multiple representations in the optics assessment instrument.

6.3.3 Contexts

The instructor had taught this course for more than 10 years. He integrated many different representations, such as diagrams, graphs, verbal descriptions and mathematical formulas, in his lectures and tutorials to help students visualize and understand physics concepts. However, as in many introductory science courses, there were limited opportunities for the students to discuss their own ideas or representations during class time. The Optics was one of six main topics taught in the 12-week course of introductory physics for non-major students. The students had five 50-min lectures, one tutorial and one laboratory session for optics. The tutorials and the laboratory sessions allowed time for discussion of the concepts presented in the lectures.

6.3.4 Optics Instrument Development

We designed 12 assessment items based on the conceptual contents and the multiple representations used in the lectures and tutorials (available from the first author). We included key concepts in optics, such as concave, convex, and plane mirror reflections, Snell's law, polarized sunglasses, etc., with a prompt for students to use as many representations as they could. The content validity of these items was ensured in meetings with three experts in physics or physics education, and consequently a marking key was developed.

The first pilot study revealed that most students used only one representation and were not sure of the definition of representation. For the second pilot study, we explicitly explained the meaning of representation and prompted students to use multiple representations; we included an introduction page with an example of a question and responses to give students an idea what was expected. We pre-selected two to four suitable representations to answer a question and designated enough blank space for a response with each representation. Nine items included three representations (word, diagram, and formula), two items with two representations (word and diagram), and one item with all four representations (words, diagrams, formulas, and coordinate graphs). The instrument items were checked again by three of the researchers to ensure the content validity and the suitability for the students.

6.3.5 Optics Instrument Administration and Scoring

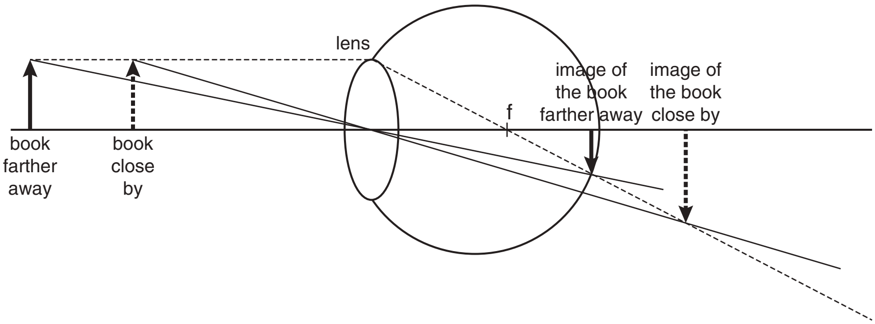
In the second year of the study, we distributed the instrument to students on two separate occasions as pre and post-tests. Pre-tests were distributed during the week before the instruction started, and post-tests were distributed immediately after the module instruction had finished. There was no time limit for students to complete

4. Why do older people who do not wear glasses read books farther away from their eyes than do younger people?

(1) Please explain your answer using words.

Because those older people have the problem of farsightedness, when they read books in a normal distance (about 25cm), the image will be formed behind retina and cannot be perceived. Therefore, they read books farther away from their eyes and the image can be formed on their retina.

(2) Please sketch a diagram(s) to help your explanation.



(3) From formulas in page 2, which formula(s) can help your explanation? How can this (these) formula(s) help your explanation?

$$\frac{1}{f} = \frac{1}{do} + \frac{1}{di}$$

In this case,

f: focal lengths of lens do: distance from book to lens di: distance from lens to image

f remains the same, so when do becomes larger, di will become smaller.

Fig. 6.1 An example of model answer for marking students' responses

answering the questions. Students were asked not to refer to any materials and not to discuss with other people. Students were encouraged to participate in this study by gaining extra credit towards their final grade; this resulted in more responses than would otherwise have been the case.

To take into account of the wide range of student responses, we allowed intermediate responses with a maximum of three for each representation (0: wrong, 1: mostly wrong, 2: mostly right, 3: correct) based on the model answers such as the one shown in Fig. 6.1. To increase the accuracy of scoring, four researchers initially evaluated eight students' responses independently and met together to discuss any disagreements in each other's marking. After the four markers came to the agreement about the allocation of marks, one person marked all students' work based on this agreed scoring rubric. In this chapter, we present data from 70 students who were enrolled in Introductory Physics in one semester and completed both pre- and post-tests.

6.3.6 Student Interviews

To gain further insight into students' perspectives on their use of multiple representations, we interviewed the same students at the end of the semester. We used their individual responses to the assessment instrument questions as a prompt for the interviews. The interviewer asked students to elaborate on their answers, their use of multiple representations for learning, and any useful or non-useful aspects in using them. Each interview session lasted for 20–35 mins. All interview sessions were recorded and their responses to the main questions were tallied in a spreadsheet. Ten interview sessions with more articulate students were fully transcribed, some of which are reported here.

6.4 Results

6.4.1 Students' Use of Multiple Representations (Research Question 1)

Before students learnt the optics content, many used words as the primary representation to respond to the question (80%). Despite ray diagrams being crucial to solve optics questions, ray diagrams were less frequently used (56%) than words. Formula was the least favorite representation and less than 20% of students adopted formula to answer the questions. The average number of students who used each representation to answer the question items are shown in Table 6.1. The frequency of responses with specific representation combinations for each item was calculated and shown in Table 6.2. A great majority of items were answered with two representations (word and diagram, 44%), followed by one representation (word only, 15%) and three representations (word, diagram, and formula, 13%).

After learning the content, students attempted to include more multiple representations in their responses. As shown in Table 6.1, more students provided their responses for each representation category. Out of four representations, more students adopted a formula in the post-test (69%) compared to the pre-test (19%). As shown in Table 6.3, students' use of a formula to answer the questions, resulted in the three-representation combination of word, diagram, and formula (49%) being the most frequent combination of representations for the post-test; the combination of word and diagram (29%) was the next most frequent combination. As seen in Fig. 6.2, the overall number of representation combination was increased for the

Table 6.1 Frequency of responses to answer each item (N = 70)

Average frequency of responses	Written words (12 items)	Diagram (12 items)	Formula (10 items)	Graph (1 item)
Pre-test	56	46	13	53
Post-test	66	60	48	56

Table 6.2 Frequency of responses with specific representation combinations for pre-test (N = 70)

Number of representations	Representation combinations and frequencies					
All 4 representations	W+D+F+G					
	16					
3 representations	W+D+F	W+D+G	W+F+G	D+F+G		
	113	33	0	0		
2 representations	W+D	W+F	W+G	D+F	D+G	F+G
	373	7	2	1	0	0
1 representation only	W	D	F	G		
	128	16	1	2		
No attempt (0 representation)	148					

Note: 70 students * 12 items in instrument (total number of responses = 840)
W words, *D* diagram, *F* formula, *G* graph

Table 6.3 Frequency of responses with specific representation combinations for post-test (N = 70)

Number of representations	Representation combinations and frequencies					
All 4 representations	W+D+F+G					
	40					
3 representations	W+D+F	W+D+G	W+F+G	D+F+G		
	415	13	1	0		
2 representations	W+D	W+F	W+G	D+F	D+G	F+G
	243	20	1	1	0	0
1 representation only	W	D	F	G		
	56	5	2	1		
No attempt (0 representation)	42					

70 students * 12 items in instrument (total number of responses = 840)

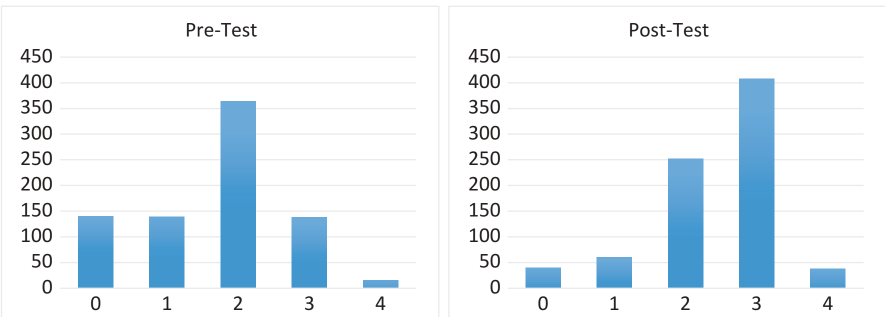


Fig. 6.2 Comparison of the number of representations for pre- and post-tests

post-test. The mode was moved from two representations to three, and the frequency of single representation or no response was greatly reduced as well.

The reliance on the text and diagrams seems to stem from the particular nature of the optics topic itself. Many students are used to providing a comprehensive written explanation in science tests. As demonstrated in any physics textbooks, ray diagrams are essential to obtain or examine the answers in optics and students were asked to draw a ray diagram when answering the questions. In the interviews, several students mentioned the important role that ray diagrams play in getting the answers to the questions and other students also mentioned the complementary role that each representation plays in describing the optics phenomena.

> Just visually seeing how the way the light rays move […] you can work out roughly what the answer should be […] you know that the answer you get is roughly what you're expecting. (Walter, a mature age student majoring in applied geology)

> The drawing of the polarized light kind of [helped me get the right answer] because if you drew in the arrows, then you'd know that as it comes through this way, the light is polarized in a certain way, and then 90 degrees to that angle. (Elizabeth, a student majoring in human biology)

On the other hand, the representation of formula was not functional to many students in answering the question for the pre-test. Students either did not write any relevant formula to a particular question or just listed a formula without explaining how it is related to the question situation. This is not surprising considering that many physics students tend to select a formula based on the given variables in the question and then plug the numbers to get the answers without considering how the formula is related to the question situation (Van Heuvelen 1991). The question items in this assessment instrument intentionally did not contain many numbers and this might have discouraged students from identifying related formula. Once students learnt the content, however, more students included formula in their responses to appear scientific.

> I explain most using words just because to explain my own understanding of it and then I tried to give the image to help my explanation or to back it up in case it wasn't clear enough how I wrote it. And then to justify it I tried to use a formula so that it wasn't just my point of view but it also had like a scientific basis. I tried to accommodate the two [representations]. (Allison, a student majoring in human biology)

In terms of students' scores for pre- and post-tests, students got higher scores in the post-test than the pre-test for each representation category and this improvement was statistically significant with Cohen's effect size from 0.58 to 1.49 as shown in Table 6.4. The students' pre-test scores ranged from a mean per student response of 0.31 (formula) to 0.89 (words) with the mean post-test student response improving to 1.00 (diagram) and 1.40 (words). The physics instruction had a relatively large effect size (Cohen's d) on students' performance, ranging around 0.58–1.49. However, regardless of the improvement of scores, all scores were calculated with reference to the maximum score of 3, meaning students' understanding of the tested concepts was not at a high level. This could be explained by the difficulties that

Table 6.4 Scores of pre and post tests for each representation (N=70)

	Pre-test	Post-test		
Type of representations	Mean (STD)	Mean (STD)	t-test (2-tailed)	Cohen's *d*
Written words	0.89 (0.41)	1.40 (0.40)	10.12***	1.26
Diagram	0.58 (0.38)	1.00 (0.45)	7.21***	1.01
Formula	0.31 (0.52)	1.13 (0.58)	10.72***	1.49
Coordinate graph	0.59 (1.16)	1.36 (1.48)	4.43***	0.58

***$p < 0.001$

students perceived when they used these different representations. This issue is discussed in the next section.

6.4.2 Students' Perception on the Benefits and Difficulties of Using Multiple Representations (Research Question 2)

Even though many students did not use all four representations successfully, the majority of students expressed the view that the assessment items with explicit emphasis on multiple representations were beneficial for them in gaining a better understanding of the optics concepts. When they were asked about the benefits of using multiple representations to answer the questions, most students stated that they had gained a better understanding (78%) whereas a minority (22%) stated that they did not see the benefit of using multiple representations in terms of building a better understanding. When they were asked if answering the assessment items helped them connect the different aspects of the concepts to solve the problem, the majority of students (84%) stated that it helped them to make the connections, 14% saying only for some of the questions while 2% stating that they could not make any relations. In the following interviews, students elaborated how they recognized the benefit of integrating multiple representations as a motivator for building deeper understanding.

> Well, to me, if it was just a question and if it didn't force us to sketch a diagram… I'm really fine giving you the equations [as the answer] because equations are in the book. [Usually,] I'm not going deeply through [the physics textbook] to study diagrams all day and these things [representations]. And then it was still annoying because I didn't know what to write properly and what to draw. […] If you don't go and study deeply, you don't get the diagrams, unless you think. (Edward, a mature age student majoring in science)

> Well it got to show me how much I don't know for one – and the things that I do know, it reinforced. And it also allowed me to know that I can draw a diagram and have a formula for things. …. Yeah it was actually really good for that, sometimes it's easier to draw a picture than do it in words. But I found it very good actually, very good for reinforcement. (Elizabeth, a student majoring in human biology)

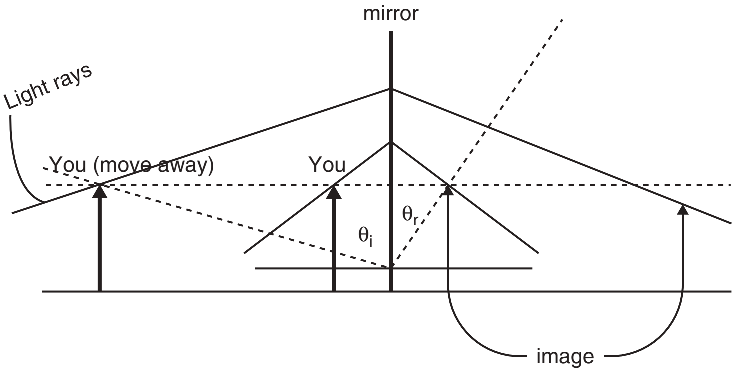
While the integration of the different representations did help most students to relate those representations and build deeper understanding, challenges still existed, as shown in Sally's case. Sally was a first year university student majoring in occu-

3.2 Will the height of your image change when you move away from the mirror?

(1) Please describe your answer using words.

No Yes, as move back, the image too "moves back", stays the same height.

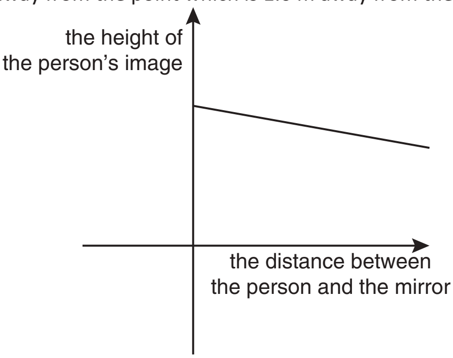
(2) Please sketch on the diagram below to help explain your answer. [Also show the necessary label(s)].



(3) Is (Are) there any formula(s) which can help explain your answer? How can this (these) formula(s) help your explanation?

do=di or θi=θr
hi=do

(4) Please complete this coordinate graph representing the situation a 2.0 m-high person walks away from the point which is 1.0 m away from the plane mirror.



as d↑, h↓

Fig. 6.3 Sally's responses to item 3.2

pational health and safety. She did not take Year 12 physics but diligently attended every lecture and tutorial. In the interview, the interviewer asked about her drawings for a plane mirror question, and she faced difficulties explaining her representations shown in Fig. 6.3. She believed she understood the concept, but when asked to draw a ray diagram and a graph, she was not able to apply her understanding to accommodate the particular requirement of the representations.

> I was a bit confused about what happens with a plane mirror. So, I know, *I just know that with a plane mirror it's always the same height. I just know that, so drawing it was actually a little bit difficult for me,* so I had to say, well if the light ray comes from wherever, it could come from wherever it might be. It could come this way; it's always going to be the same angle of incidence equals the same angle of reflection. So it's always going to come back to the same spot on the other side. Does that make sense? Which is here, the angle of incidence equals the angle of reflection.
>
> I can relate to this one [formula]. I know that this one [formula], the distance of the object is there, […] for a plane mirror for me. I can't relate to the graph. I had to think about this because… so coordinate graph, all I know is that, the graphs don't mean anything to me.

From Sally's response, her confusion was obvious. Her written and verbal statement that the height of image on a plane mirror stays the same seemed to be from memorizing, which was consistent with findings in the literature (Van Heuvelen 1991). While she managed to use words to represent the scientific understanding, her graph clearly showed that she was not able to consolidate the scientific understanding with her everyday experience of seeing an object smaller in distance. The coordinate graph showed the height of the person's image becomes less and less as the distance between the person and the mirror increases. However, when she was explaining her graph, she dismissed it as if she did not care too much about it. In addition, her lack of competence in using ray diagrams and relevant formula was not helping her solve the problem successfully. Her diagram showed that she had problems with the syntax of light ray diagrams. The light rays in the diagram are drawn as if they are traveling in an erratic way to make it difficult to understand how the images form. The angles of incidence and reflection ($\theta\iota$, θr) were stated as the same in the interview and in the formula section, but they were drawn differently in the diagram section. Because she did not feel competent enough to seek the coherence of different representations or integrate them in her explanation, she did not gain the full benefit of using multiple representations to build more scientific understanding.

A similar situation is illustrated by Grace, a student majoring in human biology, in reference to item 7.2 in the optics instrument shown in Fig. 6.4. The question is about the image in a convex mirror, which she found confusing.

> You had to say whether the image changed when you move away from the convex mirror. I know the image size should change, but I didn't know which way it would change, whether it would increase in size or decrease in size. And I didn't know how to draw the ray diagrams. So therefore, using a diagram, it was hard to come up with whether it would increase or decrease. Then if you used the formula, it said if your distance of the object increases, then your height should decrease.

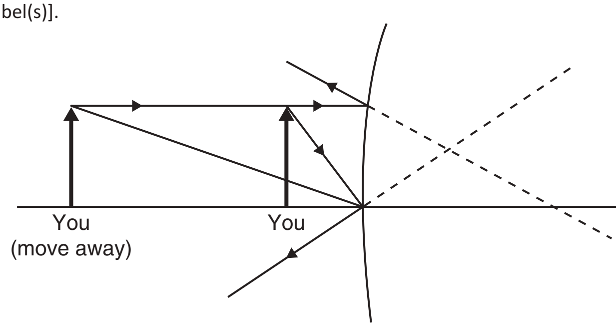
Grace knew that the height of image would change when the object moves away from the convex mirror, but she did not know how the height of image would change and why using ray diagrams. Even though it is critical to be able to draw ray diagrams when learning optics, she had trouble in drawing ray diagrams and finding the answer to the question. However, she was competent at using her formulas to solve the problem and managed to explain how the image size would change with a formula. However, she did not go back to the ray diagram to illustrate her answer. If her understanding of syntax and domain of ray diagrams had been sufficient to rea-

7-2. Will the height of your image change when you move away from the convex mirror?

(1) Please describe your answer using words.

Yes, the height of the image changes when you move away from the convex mirror, because the distance of the object changes, thus the height changes.

(2) Please sketch on the diagram below to help explain your answer. [Also show the necessary label(s)].



(3) Is (Are) there any formula(s) which can help explain your answer? How can this (these) formula(s) help your explanation?

$$m = -\frac{di}{do} = \frac{hi}{ho}$$

Fig. 6.4 Grace's responses to item 7.2

son about the height of images, or if she was confident that her answer from the formula was applicable to the ray diagram, her understanding would have become more comprehensive.

In short, based on an analysis of the interviews and the excerpts presented above, these students believed that being asked to integrate multiple representations was beneficial for them to build more scientific understanding of the optics concepts. However, the level of knowledge in the syntax and domain of each representation influenced the level of integration of different representations. The demand for the competence in each representation could vary depending on different science topics. For optics, this study shows, the ray diagrams and formulas should be given more attention in the instruction which agrees with previous studies. The emphasis on some specific representations does not mean other representations are worthless. The instructors can arrange the priority of different representations in their instruction based on the topics they teach.

6.5 Conclusion

In this study, we developed and administered an optics assessment instrument to ascertain students' understanding of optics concepts in relation to illustrating what they know by using four different representations of the concepts under consideration. The students' responses on the post-test had improved compared to the pre-test, with the majority of students using two representations – word and diagram – to three-representations – word, diagram, and formula. While there was an improvement of use of multiple representations, when these responses were scored, all scores, with reference to the maximum score of 3, were low, meaning that students' understanding of the tested concepts was not at a high level. Despite this lack of competence in using multiple representations, students reported in interviews that the assessment instrument using the text descriptions, diagrams, formulae and graphs provided positive feedback for them to improve their own knowledge.

However, they also revealed some challenges and difficulties while learning with the multiple representations. Even when the lecturer seamlessly integrated multiple representations in lectures and the majority of students claimed that they recognised the benefits of integrating multiple representations for their learning in this introductory physics topic of optics, many students considered that it was still difficult to answer the questions using all four multiple representation. In this Introductory Physics class for non-physics majors, as in previous research with introductory physics courses, the students had insufficient background knowledge of the physics concepts and were not able to make use of multiple representations effectively (see for example, van Someren et al. 1998). Also multiple representations pose increased cognitive demands on learners (Sweller 1994).

Once students have the ability to use the different representations and the meaning they represent within that representation, it will be much easier for them to integrate or translate different representations to have a deeper understanding of the concepts. Representational instruction, including explicit instruction on the syntax and domain of each representation, and the relation between representations using as many as examples as possible is strongly recommended for students to learn optics with integrated multiple representations. A practical and important outcome from the use of the items in the multiple-representation instrument used in this study is that while the items were designed to elicit students' multiple representations about problems in optics, the instrument can also be used as an alternative tool for measuring students' conceptual understanding.

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Chapter 7
Enacting a Representation Construction Approach to Teaching and Learning Astronomy

Peter Hubber and Russell Tytler

7.1 Introduction

There is increasing attention being given to the role of representations in learning science as part of growing recognition of the representational basis of knowledge creation in science and generally (Latour 1999). Quality learning must involve richer and more sustained reasoning and engagement with the mediating tools of the discipline in ways that entail the acquisition of a subject-specific set of purpose-designed literacies (Lemke 2004; Moje 2007). There is an increased focus on students learning how to reason through visual, linguistic and mathematical modes. Much of recent research has placed emphasis on students learning to use scientific representations flexibly to visualize phenomena and problem solve. Students use the multi-modal representational tools of science to generate, coordinate and critique evidence (Ford and Forman 2006), involving models and model-based reasoning (Lehrer and Schauble 2006).

This study relates to a guided inquiry approach to teaching and learning, called representation construction, involving students constructing and negotiating multiple representations through sequences of representational challenges. Guided inquiry is defined as an intermediate teaching approach fitting between open-ended, student-directed learning and traditional, direct instruction (Furtak 2006). The research is part of a wider program, an Australian Research Council (ARC) funded project titled Creating Representations in Science Pedagogy (CRISP 2012–2015), which investigates the professional learning of teachers developing a representation construction approach. The study involves the planning and implementation of a unit on astronomy by a community of four secondary school teachers. This research aimed to document the experience of the teachers in implementing a representation

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construction approach, and to investigate the quality of student learning associated with different aspects of the pedagogy.

7.2 Development of the Representation Construction Approach

A recent ARC funded project (2007–2010), Representations in Learning Science (RiLS), developed a theoretically sophisticated but practical, representation construction approach to teaching and learning that links student learning and engagement with the epistemic (knowledge production) practices of science (Tytler et al. 2013a). This approach involves challenging students to generate and negotiate the representations (text, graphs, models, diagrams) that constitute the discursive practices of science, rather than focusing on the text-based, definitional versions of concepts. The representation construction approach is based on sequences of representational challenges, which involve students constructing representations to actively explore and make claims about phenomena. It thus represents a more active view of knowledge than traditional structural approaches and encourages visual as well as the traditional text-based literacies.

In developing this particular approach to guided inquiry teaching in science and in interpreting the nature of learning that flows from it, our perspective follows pragmatist accounts of the situated and contextual nature of problem-solving and knowledge generation (Peirce 1931–1958; Wittgenstein 1972). We understand a pragmatist orientation as an empirical and systematic method of inquiry that involves a collective analysis of experience to establish reasoned knowledge, avoiding a priori judgments. In this account representations actively mediate and shape knowing and reasoning such that classroom teaching and learning processes need to focus on the representational resources used to instantiate scientific concepts and practices. In traditional accounts, representations are often cast as efficient and effective ways to introduce and illustrate abstracted concepts that are conceived of as distinguishable from the representations through which they are generated and communicated. From our perspective however, representations are the reasoning tools through which we imagine, visualise spatial relations and model astronomical phenomena. This view is also fundamentally Vygotskian, characterising representations as the disciplinary language tools that mediate thinking and knowing (Moje 2007).

Accounts of scientific knowledge producing practices emphasise the fundamental importance of visuo-spatial representations in the imaginative practice of discovery (Gooding 2004), and the way that data is transformed into knowledge through a series of representational "passes" (Latour 1999; Nersessian 2008). In this way we argue that the epistemological processes central to this representation construction inquiry approach mirrors the epistemic practices of science itself (Prain and Tytler 2012).

RiLS has successfully demonstrated enhanced outcomes for students, in terms of sustained engagement with ideas, and quality learning, and for teachers' enhanced pedagogical knowledge and understanding of how knowledge in science is developed and communicated (Hubber 2013, 2010; Hubber et al. 2010). This representation construction approach shows promise of resolving the tension between inquiry approaches to learning science and the need to introduce students to the conceptual canons of science (Klein and Kirkpatrick 2010).

7.2.1 Principles Underpinning the Representation Construction Approach

The set of principles (Tytler et al. 2013b, p. 34) developed by the RiLS project that underpin the representation construction approach to teaching and learning are described as:

1. **Teaching Sequences are Based on Sequences of Representational Challenges**
   Students construct representations to actively explore and make claims about phenomena.

   (a) **Clarifying the representational resources underpinning key concepts**: Teachers need to clearly identify big ideas, key concepts and their representations, at the planning stage of a topic in order to guide refinement of representational work.
   (b) **Establishing a representational need**: The sequence needs to involve explorations in which students identify the problematic nature of phenomena and the need for explanatory representation, before the introduction of the scientifically accepted forms.
   (c) **Coordinating /aligning student generated and canonical representations**: There needs to be interplay between teacher-introduced and student-constructed representations where students are challenged and supported to refine and extend and coordinate their understandings.

2. **Representations Are Explicitly Discussed**
   The teacher plays multiple roles, scaffolding the discussion to critique and support student representation construction in a shared classroom process. Students build their meta-representational competency (diSessa 2004) through these discussions.

   (a) **The selective purpose of any representation**: Students need to understand that a number of representations are needed for working with multiple aspects of a concept.
   (b) **Group agreement on generative representations**: There needs to be a guided process whereby students critique representations to aim at a resolution.

(c) **Form and function**: There needs to be an explicit focus on representational function and form, with timely clarification of parts and their purposes.
(d) **The adequacy of representations**: There needs to be ongoing assessment (by teachers and students) of student representations as well as those representations introduced by the teacher.

3. **Meaningful Learning**

   Providing strong perceptual/experiential contexts and attending to student engagement and interests through choice of task and encouraging student agency.

   (a) **Perceptual context**: Activity sequences need to have a strong perceptual context (i.e. hands on, experiential) and allow constant two-way mapping between objects and representations.
   (b) **Engagement /agency**: Activity sequences need to focus on engaging students in learning that is personally meaningful and challenging, through affording agency and attending to students' interests, values and aesthetic preferences, and personal histories.

4. **Assessment Through Representations**

   Formative and summative assessment needs to allow opportunities for students to generate and interpret representations. Students and teachers are involved in a continuous, embedded process of assessing the adequacy of representations, and their coordination, in explanatory accounts.

These principles formed the basis of the current Constructing Representations in Science Pedagogy (CRISP) project (2012–2015) which aims at wider scale implementation of the representation construction approach. In introducing the approach to new teachers the CRISP researchers aim to identify key enablers, and blockers, that facilitate quality teacher learning and adaptation of the representation construction approach. This chapter documents the experiences of four Year 8 teachers from a Melbourne metropolitan private school who were initially introduced to the representational construction approach and then implemented the approach in a four-week teaching sequence in the topic of astronomy.

7.3 Research on Students' Understanding of Astronomy

The significant amount of research into individuals' understanding of astronomy in recent decades has found that conceptions of the Earth and day-night cycle are relatively well understood by secondary school students, while the Moon phases, the seasons and gravity are phenomena that students, and adults, find difficult to understand and explain (Danaia and McKinnon 2008; Kalkan and Kiroglu 2007; Lelliot and Rollnick 2010; Trumper 2001). Common alternative conceptions found among students include: the phases of the moon are caused by the shadow cast on the Moon due to the Earth obstructing the light from the Sun; the seasons are caused by variations in distance between the observer on Earth and the Sun; and, gravity does not operate in the absence of air.

The prevalence of alternative conceptions for individuals across most age levels may suggest that school science has limited impact in resolving them. Bakkas and Mikropoulos (2003) point out that the sometimes limited success of conventional teaching methods in overcoming students' alternative conceptions may be due to a lack of appropriate teaching aids in the form of representations that can intervene dynamically in the learning process and modify it.

Astronomical phenomena such as the seasons and phases of the moon are difficult for students to understand as they involve an understanding of three dimensional spatial relationships and orientations between celestial objects (Hegarty and Waller 2004; Padalker and Ramadas 2008; Yu 2005). Constructing explanations for astronomical phenomena requires learners to understand motion across frames of reference, coordinating Earth-based perspectives and space-based perspectives. A full explanation requires an ability to shift between these perspectives to explain the patterns in observations made from a rotating Earth and the actual motions and orientations of the objects in space (Plummer 2014).

The teaching of astronomy needs to develop students' spatial visualization (the ability to imagine spatial forms and movement, including translation and rotations) and spatial orientation (perspective taking) (Padalker and Ramadas 2008; Hegarty and Waller 2004). These skills may be enhanced through carefully planned activities which use physical models and modelling as a key part of the pedagogy (Lelliott and Rollnick 2010). Plummer (2014) suggests that students' spatial thinking can be improved through activities whereby students create spatial representations (maps, graphs, 3D models, gestures, etc.).

In this study we worked with the Year 8 teachers to plan and research an astronomy unit that used our guided inquiry approach in which students constructed and explored representations of the sun-earth-moon system. This approach is consistent with recommendations from the literature, described above, and in our planning with teachers we explicitly sought to address these learning difficulties associated with coordinating earth and space perspectives, described above. Our aim was to investigate the teachers' experience of developing and refining the approach, the quality of learning arising from the approach, and teachers' perceptions of the key aspects of the pedagogy that led to deeper learning. Our research questions were:

1. What are teachers' perceptions of the effectiveness of the representation construction approach in supporting student learning of astronomy?
2. What aspects of the approach do teachers perceive as key to its support of student learning?
3. What evidence is there that the approach leads to quality learning of astronomy?

7.4 Methodology

The research reported in this chapter sits within the wider CRISP study which aims to develop and refine a professional learning approach that is effective in establishing a guided inquiry approach to teaching and learning science based on representation construction. The methodology is one of Design Based Research (Collins et al. 2004) in which the intent is to systematically develop and refine ways of working with teachers to effect changes in their epistemological and pedagogical beliefs and practices. Design based research has a dual focus on theory development, and development of contextually appropriate processes. Design experiments are typically 'test beds' for innovation and the theory they develop must do real work, in the pragmatic tradition (Cobb et al. 2003). Design experiments are characterised by a cyclical process of refinement and evaluation with the data generated being often messy and multi layered, being grounded in complex teaching contexts, often involving a mix of qualitative and quantitative data. Within CRISP the research is conceptualised as a partnership between teachers and researchers, with teachers participating in workshop discussions concerning the efficacy of the approach and ways of refining it to further improve student learning. Teachers have on a number of occasions co-presented with the research team at conferences.

For the particular 'design experiment' described here, the focus is not on the change process but on investigation of teachers' perceptions of the pedagogy and its effectiveness, as part of the design cycle. The methodology is predominantly ethnographic, exploring the nature of the teacher-student interactions, and teachers'experience of planning and implementing a representation construction sequence in astronomy, and their reflection on their experience and the outcomes for students. The data includes illustrative examples of student work. It also includes records of the research team's analysis discussions in which themes were identified and refined.

As mentioned previously there were four Year 8 teachers who taught a four-week teaching sequence in astronomy to 5 classes of boys (class size 28–30 students). In exploring teachers' experience of the representation construction approach the following data generation instruments were used:

- Pre- and post-tests;
- Planning documents and teaching resources;
- Classroom video of one lesson of each of the three of the teachers – the lesson was chosen by the teacher;
- Recorded, and transcribed, teacher and selected student interviews following the teaching sequence;
- Student artefacts, in particular, their project books which contained a record of their responses to many of the representational challenges as part of the representation construction approach;
- Recorded, and transcribed, conversations among the Deakin CRISP team and teachers in planning meetings prior to the teaching sequence and every week of the teaching sequence; and

- Whole day review with CRISP researchers and teachers that involved studying student work and selected video segments of the teachers. The workshop review also included discussions about the teachers' perceptions of the representation construction pedagogy in relation to their practice. The review was recorded and transcribed.

The principles of the representation construction approach, described above, were used as an analysis framework to interpret the features of teacher student interactions, to explore the particular ways in which these principles played out in the astronomy sequence and the fidelity of these teachers' work to the approach. Teachers' perceptions of the approach, of its particular affordances, and of student learning gains, were analysed through the identification of themes that were developed from the interview and workshop discussion data, through discussion amongst the research team and in collaboration with the teachers.

7.4.1 The Study Design

Salsa College is an all-boys metropolitan Catholic secondary school in a middle class area of an Australian city, with student enrolment around 950. There were four teachers (Alice, Suzy, Kate and Jaz)[1] who taught five Year 8 classes (class sizes of 28–30) the topic of astronomy over a 4-week teaching sequence. There was 160 mins of class-time each week that consisted of an 80 min lesson and 2 x 40 min lessons. One of the classes was special entry (high academic achievement) taught by Alice; two of the classes were taught by Kate and the other two classes by Suzy and Jaz. All teachers were quite experienced, Suzy and Jaz had taught at Salsa College for several years, Alice was in her first year at Salsa College and Kate was in her first Term at the school. The topic of astronomy dealt with explanations associated with such phenomena as day/night cycle, phases of the moon, seasons, gravity and eclipses. The intention was to address the new Australian Curriculum: Science (ACARA 2010) and so the content of this topic matched this curriculum.

The teachers were provided with curriculum resources and professional development that was delivered in various forms by the Deakin CRISP team. Each of the teachers was given curriculum resources that were based on the findings from the teaching of this topic using the representation construction approach in one of the schools which took part in the original RILS project. These resources consisted of pre- and post-tests, written descriptions of various activities that illustrated the representational construction approach, examples of student work from the RILS project and digital resources in the form of PowerPoint presentations with embedded interactive simulations and video.

In addition to these resources Alice had already had prior knowledge of the representational construction approach through participation in a 3-day state-wide

[1] Pseudonyms are used for the school and teachers cited in this chapter.

professional learning program that had a focus on the representation construction approach and was funded by the Victorian (Australia) Department of Education. Suzy and Jaz had undertaken a 2-hour after-school workshop delivered by the CRISP researchers to the science staff at Salsa College. In both the state-wide professional learning program and the workshop importance was placed on the University experts modelling the representation construction approach.

The support given to the teachers also consisted of weekly meetings during the teaching sequence where the CRISP researchers and teachers had reflective discussions as to the previous week's teaching in addition to planning the future week's teaching. The four teachers involved in the CRISP project worked closely with the CRISP researchers in unit development, but ultimately were responsible for the operation of the ideas in the classroom.

7.5 The Representation Construction Approach in Teaching Year 8 Astronomy

This section describes the four-week astronomy sequence as it occurred at Salsa College in the four teachers' classes. Links are made between the various activities and the key elements of the representation construction approach, to clarify the central features of the pedagogy.

In enacting a representation construction approach importance needs to be given at the planning stage to the determination of the key concepts that underpin the topics to be taught [Principle 1a]. These concepts are expressed as statements of understanding couched in language readily understood by the students. At the planning stage of the topic the CRISP researchers worked with the Salsa teaching in developing a set of key concepts that would underpin the teaching and learning of astronomy. For example:

- Day and night are caused by the Earth turning on its axis every 24 hours,
- The seasons are caused by the changing angle of the sun's rays on the Earth's surface at different times during the year (due to the Earth revolving around the sun). This means for observers from Melbourne:
  - The midday Sun in summer is higher in the sky than the winter Sun. It will never be directly overhead at any time of the year.
  - The hours of daylight are longer in summer than in winter.
  - The average temperatures are hotter in summer than in winter.

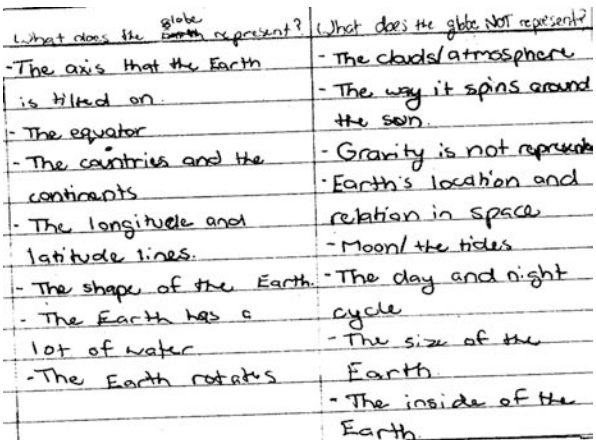
The epistemological position underpinning the representation construction approach is that concepts such as these, traditionally couched in formal verbal terms, need to be understood as standing for a set of interlinked representations and practices. Thus, these statements of understanding guided CRISP researchers and Salsa teachers in the development of the representational resources and strategies to use in teaching each concept. The statements also guided the teachers in developing a set of representational experiences that provided students with a coherent link between the concepts.

The teaching sequence began with pre-testing of the students' understanding of the key concepts. The administration of pre-tests were not common at Salsa College but the prevalence among the students of common alternative conceptions exposed by the pre-test, consistent with the student conceptions research literature, informed teachers classroom strategies. This is illustrated by the following comments by Alice:

> I asked the ones, that I knew had misconceptions, to put them up on the board. And then we kind of discussed, alright, so now we know this is the case, do we have to change these representations? And it was really good, because then they would go "Yeah we do actually, this needs to be changed." … we weren't pretending like they had this blank slate and they'd never seen astronomy before. They already had ideas, that we kind of – half the battle was challenging them, more so than teaching them new content. [Alice]

The teaching sequence for each of the classes proceeded with a critique of the globe as a canonical representation of Earth in space. Students were given the task to determine those characteristics of Earth that were represented by the globe in addition to determining those characteristics of Earth that were not represented by the globe [Principle 2d]. Once lists were compiled by the students (see Fig. 7.1) they formed the basis of a whole class discussion.

From these discussions the phenomenon of the Earth's tilt was discussed. Analysis of the video record of class discussions, and records of discussions with teachers in review meetings, indicated that most students felt the tilt was with respect to the vertical thus explicating an earth frame of reference rather than considering the space frame of reference. One teacher resolved this by making explicit references to the two frames of reference. This was done by placing the students into a space view and modelling Earth's rotation around the sun with a globe



What does the ~~Earth~~ globe represent?	What does the globe NOT represent?
-The axis that the Earth is tilted on.	- The clouds/atmosphere
- The equator	- The way it spins around the sun.
- The countries and the continents	- Gravity is not represente
- The longitude and latitude lines.	·Earth's location and relation in space
- The shape of the Earth.	- Moon/the tides
- The Earth has a lot of water	- The day and night cycle
-The Earth rotates	- The size of the Earth
	- The inside of the Earth

Fig. 7.1 Year 8 student's critique of a globe as a representation of Earth in space

revolving around a student representing the Sun; the Earth's tilt with respect to its plane of orbit of the sun was made apparent [Principle 2a].

The teacher then provided the students with another space frame of reference getting them to use the globe as a reasoning tool to predict observations made from Earth from a space frame of reference. A small figurine was affixed to the globe to represent an observer on Earth located in Melbourne (Australia) and a ball was used to represent the Sun. For a particular orientation of the globe with respect to the ball the students were asked:

1. Which way does the Earth spin?
2. For the position of the figurine on the globe as representative of an observer on Earth:
   (a) what time of day is being represented?
   (b) where else on Earth is it the same time of day?
   (c) what is the season?

In answering the first question one student rotated the globe and reasoned that as the Sun shines on the East coast of Australia first then the Earth must rotate in an anti-clockwise fashion. Following this activity, and in subsequent lessons, each pair of students was given access to a mini-globe and a small, but powerful, Light Emitting Diode (LED) torch. These were to be used as a reasoning tool to gain understanding of astronomical behaviours such as the day and night cycle, eclipses, seasons and phases of the Moon. For example, Fig. 7.2 shows a student response to a representational challenge to explain in their journals why when some observers on Earth can experience a total eclipse whilst others cannot. The students used the mini-globes and LED torches when undertaking this challenge [Principle 3a]. This figure is typical of higher quality student representations. Note, in the figure, the coordination of text and image, the sophistication of the reasoning, and evidence of strong, and distinctly individual engagement with the challenge task.

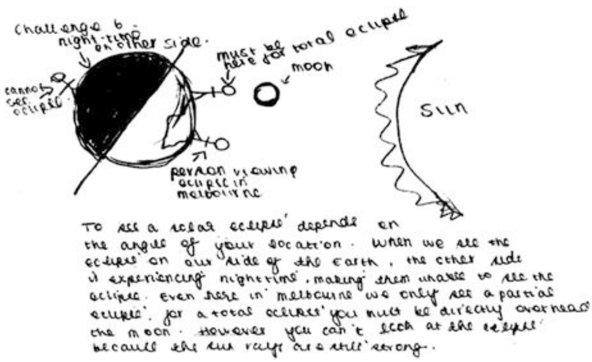


Fig. 7.2 Year 8 student's response to the total eclipse challenge

The teacher saw the use of the globe and torch as a tool to facilitate students' space-centric explanations of geocentric observations of astronomical phenomena [Principle 3, 1a, c]. Alice commented:

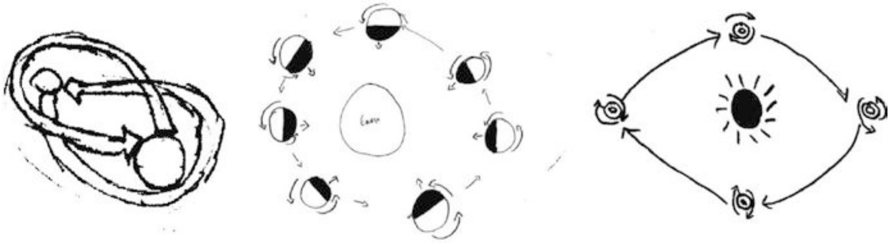
> And I think that the biggest thing, that worked really well, was the use of the globes. It had them all having the globes and actually having something physical to play with, actually made a lot of difference, in just those first few kinds of concepts, that usually, it's hard for them to get their heads around. [Alice]

The relative motion of the Earth, Moon and Sun in terms of rotation and revolution give rise to a variety of phenomena on Earth such as the day and night cycle and phases of the Moon. In exploring the motions of rotation and revolution the teacher gave the students a series of representational challenges [Principle 1]. The first challenge was for a pair of students to demonstrate, through an embodied representation, their understanding of rotation and revolution. Following a class discussion that evaluated the representation all students came to an agreed understanding of these movements and the need for a central axis for rotation and a central point for revolution and linkage of these terms with the everyday language of spin (rotate) and orbit (revolve).

The teacher then provided the students two representational challenges [Principle 1]. These were:

1. Is it possible for two celestial objects to revolve about each other?
2. The Moon always has one face to the Earth. Over one month the Moon undertakes one complete revolution of the Earth. During this time does it also rotate and, if so, how many times?

The students found that answers to these challenges could only be obtained through role-play [Principle 1b]. The evaluation phase of each challenges was undertaken as a whole class discussion. For the first challenge, to which the answer is yes, the teacher made a link to binary star systems where this phenomenon is found. For the second challenge, many of the students were quite sceptical in the beginning as to whether the Moon rotated but by undertaking the role play they found evidence that the Moon does indeed rotate, making one full rotation each month. This evidence was the observation that in undertaking one full revolution the student representing the Moon observed each wall of the classroom just once, as they would if they rotated in a fixed position. Figure 7.3a shows evidence of a third challenge given to the students whereby they were to pictorially represent two objects revolving about each other. In this task students were expected to re-represent their 3D role-play representation of revolving celestial object into a 2D form [Principle 7.3b]. The teacher had a common practice that in most lessons some time was allocated at the end of the lesson for the students to represent in their journals something they had learned that lesson. Figure 7.3b shows one student's representation of the motion of the Moon whilst Fig. 7.3c shows another student's representation of rotation and revolution of the Earth's motion about the Sun. These three representations were selected to be typical of student work. They constitute a representational re-description of the role play that was used to establish the distinc-



a Revolving Suns   b Motion of the Moon   c Motion of Earth

Fig. 7.3 Year 8 representations of rotation and revolution of celestial objects. (**a**) Revolving Suns. (**b**) Motion of the Moon. (**c**) Motion of Earth

Fig. 7.4 Year 8 students representations of the noon day Sun in winter from Melbourne

tion between rotation and revolution. In each case the representation engages seriously with the representational challenge, in ways that are distinct from standard astronomical figures found in school texts.

In enacting a representation construction approach students and teachers are involved in a continuous, embedded process of assessing the adequacy of representations, and their coordination, in explanatory accounts [Principle 4]. In these classes public display and critique of the students' representations either at the whole class or small group level was an essential component to the representational challenges that were given. Kate and Alice commented on their strategies for doing this, and their effectiveness:

> I photocopied a whole lot of different kids' representations which were passed around… they had it for a minute and then it got passed on. They had to evaluate the representations …that got them thinking oh hang on, that doesn't show that. I think it does, but it actually doesn't but I think it's good. [Kate]

> I'd ask for someone to come up and then I'd ask for someone who had something different than they had up, to come up, so we ended up with like 3 or 4 different ones and then we'd look at which one did the best… and then they just debate them. [Alice]

An example of a representational challenge for the students (see Fig. 7.4) was to represent in a drawing the phenomenon that the noon day Sun does not go directly overhead during winter from the location of Melbourne (Australia). This challenge

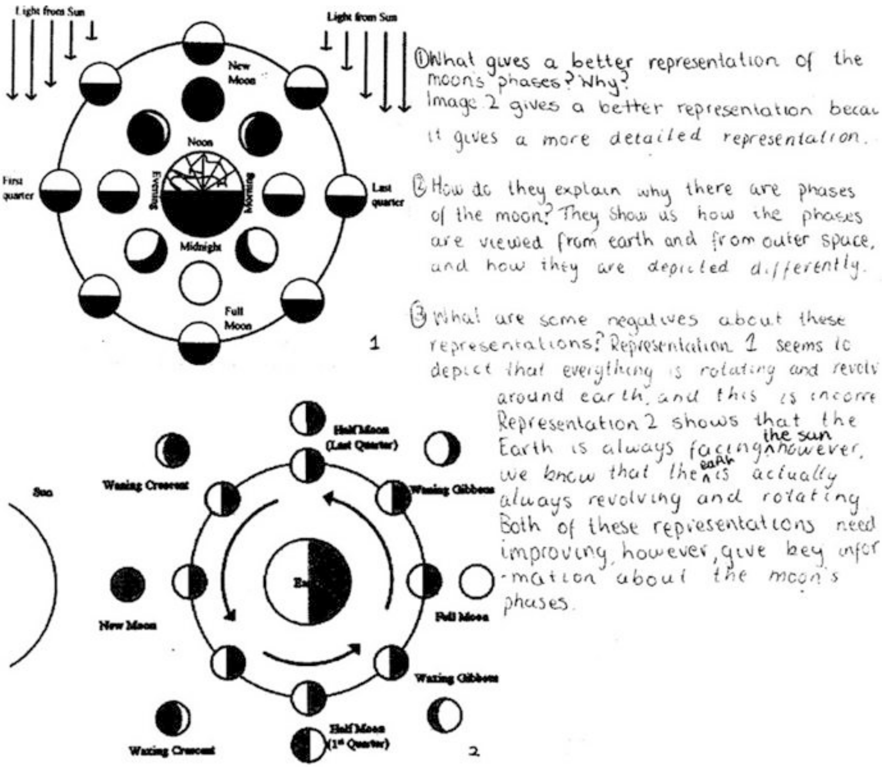


Fig. 7.5 A Year 8 student's critique of two textbook representations of phases of the moon

followed a class demonstration and discussion using 3D models representing the phenomenon. Each of the representations draws on different and distinct semiotic resources to indicate the height of the sun above the horizon.

The assessment of the adequacy of representations is a key feature of the representation construction approach. Part of the purpose is to develop students' meta-representational competence (diSessa 2004). This occasionally extended to assessment of canonical forms found in science texts and on the internet. Figure 7.5 below shows a student's journal entry of a task that involved the critique of two textbook representations of the phases of the moon [Principle 4].

In interviews and during meetings teachers frequently commented that the ample provision of space given for students to respond to representational challenges and paper-based test questions afforded the students the opportunity, and permission, to express their understanding in a variety of representational forms that are distinct in fresh ways from diagrams that are copied from texts or from the board. This was supported by analysis of student representational work. For example, Fig. 7.6 provides four students' responses to a topic test question where they were given the context that one of the moons of Jupiter was found to rotate and revolve around the planet and asked to explain the difference between representation and revolution.

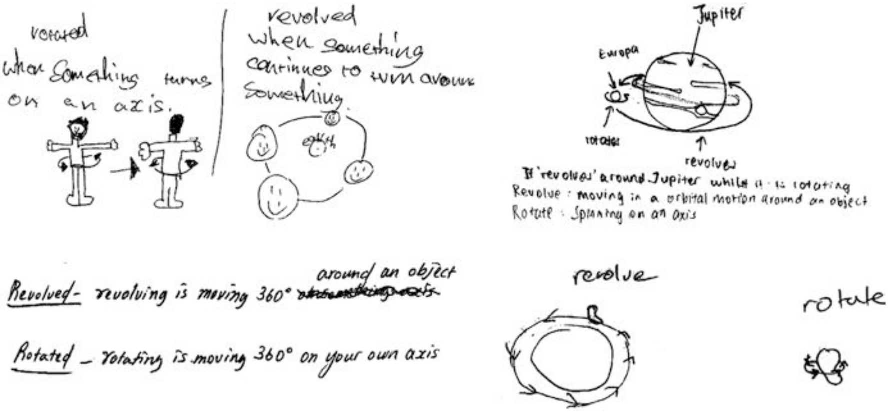


Fig. 7.6 Year 8 students' explanations of rotation and revolution

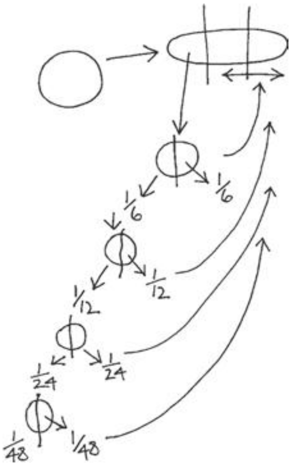
Again, each demonstrates serious attention to the task, and focused reasoning. The representations demonstrate a variety of semiotic resources; the first two, for instance combine text and drawing. They are individual, and distinctive.

The teaching sequence placed importance on developing students' concepts of size and distance of celestial objects. In constructing a solar system model on the school oval that involved students representing the Sun and the planets the class discussed the meaning of a 'year' on planets other than the Earth and speculated how far away from the school oval might the nearest star be located. In another activity students were challenged to represent the relative sizes of Earth and Moon given a handful-sized lump of plasticene. Evidence from the students' journals where they recorded their predictions showed that very few students constructed models that reflected the actual relative sizes of the Earth to the Moon. Most overestimated the size of the Moon and so the teacher gave written instructions (Fig. 7.7a) for students to construct accurate models. Most students were unable to undertake the task from written instructions so a representational need was established [Principle 2b] after which the teacher developed the diagram (Fig. 7.7b) shown which the students were able to follow. The next challenge for the students was to represent the separation of their models of Earth and Moon. All the students underestimated the distance which led the teacher to show an accurate model of the Earth, Moon and Sun both in relative size and distance. This model was then used to represent the monthly motion of the Moon around the Earth. This model gave the students a plausible representational form to explain why lunar/solar eclipses do not occur every month and offset textbook diagrams which suggest such occurrences occur regularly, since distance and scale are often not represented in the diagrams (Dunlop 2000).

Relative size of Earth and Moon

1. Join the two spheres together and roll the plasticine into a sausage shape;
2. Divide the sausage shape into three equal parts and then join two of the parts together.
3. Divide the third piece of plasticine into two halves, keeping one half in your hands and adding the other half to the larger piece of plasticine.
4. Divide the smaller piece into two, keeping one half in your hands and adding the other half to the larger piece of plasticine.
5. Repeat step 4
6. Repeat step 4
7. You should now have one small piece and a large piece. The small piece represents the Moon and the small piece represents the Earth.

a Written instructions



b diagrammatic instructions

Fig. 7.7 Instructions for creating a plasticene model of Earth and Moon. (**a**) Written instructions. (**b**) diagrammatic instructions

7.6 Main Findings

The main findings, following the research questions, relate to teacher perceptions of the distinctive features of the inquiry approach, it's role in assessing student understanding, and the impact on student learning. These major themes emerged over time, from analysis interviews and records of workshop discussions.

7.6.1 Teacher Perception of the Inquiry Approach

The teachers perceived the representation construction approach as one in which the teacher might effectively implement an inquiry approach that moves beyond text-book teaching. Core features include the freedom from text-book domination that the inquiry approach brings, and the way that the approach is distinct from open inquiry in the way it focuses on conceptual learning:

> Oh it's just reinforced that sometimes textbooks aren't the answer to all science teaching and if you mix it up I think that's the best approach rather than flogging this textbook idea. I think if you can bring something like this inquiry based learning as a different approach I think that's only going to benefit the kids' learning [Jaz].

> I think it's given us an actual tangible way to do the inquiry base that's an easier way for most staff to sort of like cause when we talk inquiry base they think open ended the kids are going to be all over the shop hey whereas this kind of gives them that ability to have inquiry learning but in a different way [Kate].

The teaching approach was perceived to be effective through the active engagement with materials and with problem tasks: "because they're learning by doing it they're not just rote learning or trying to remember facts [Kate]" and the interactive nature of the tasks: "having to explain it to someone else or to put down what they know [Jaz]".

7.6.2 Formative Assessment

The teachers used the information gained from the pre-tests in their teaching as is illustrated by the following comments:

> …we weren't pretending like they had this blank slate and they'd never seen astronomy before. They already had ideas, that we kind of – half the battle was challenging them, more so than teaching them new content. [Alice]

> I did deal with the topics that they had the most trouble with [Jaz]

The students used project books, which contained blank pages that encouraged visual forms of representation. The students used their project books more as learning journals that facilitated the use of drawings in recording not only what they had learned but their developing ideas (see Fig. 7.8 for examples). The visual representations provided the teacher with ready insight into students' thinking. One of the teachers, Alice, commented in an interview:

> Immediately by looking at their representations, I know, okay those boys have got it and those boys are on the right track but those haven't fully kind of understood (Alice)

> But the books just having the blank page, I think sometimes, it's just all text, that we kind of forget how much the use of those representations and diagrams can really help in Science, so it was a good reminder. (Alice)

Figure 7.8 shows three images from students' journals, which are typical of higher end representational work. While a formal analysis of these representations has not been undertaken, each illustrates the productive nature of representation construction in relation to features such as: (1) the coordination of multiple representations that show different perspectives brought to bear on a challenge, (2) the quality of reasoning, and particularly spatial reasoning, that is evidenced, and (3) the coordination of image and text that is characteristic also of scientific discovery processes (Gooding 2004, 2006).

The Salsa teachers had introduced the journals, in consultation with the researchers, as an innovation designed to encourage students to engage seriously with representational work. In meetings they frequently described how the students were more willing to use their journals to reflect on their learning than had been previously the case with text journaling. As Kate pointed out:

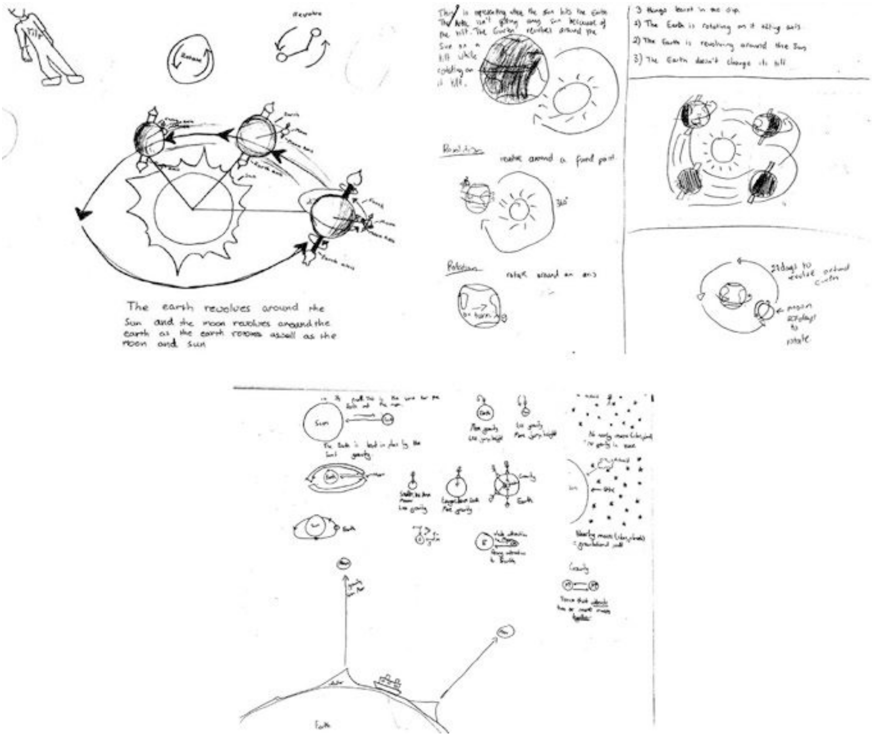


Fig. 7.8 Examples of students' learning journals entries

> …they seemed more willing to go back over their work and look back at their past stuff as well…And I don't think they do it very well if it's just written stuff, and they had a sense of ownership over it which was good (Kate)

7.6.3 Student Learning

Pre- and post-testing of the students revealed substantive gains in learning. Table 7.1 indicates substantially improved students' results to 13 multiple choice questions on the pre/post-tests. The test was a recognised instrument developed by (Trumper 2001), and in particular was used by (Kalkan and Kiroglu 2007) in a study that involved 100 pre-service primary and secondary education teachers who participated in a semester length course in astronomy. This allows us to compare results with those obtained by Kalkan and Kiroglu, using the normalised gain index, <g>, as a measure of comparison of pre- and post-test results. <g> is a measure of the ratio of the actual average student gain to the maximum possible average gain: <g> = (post% – pre%)/(100 – pre%), as reported by Zeilik et al. (1998). Gain index values can range from 0 (no gain achieved) to 1 (all possible gain achieved). For

Table 7.1 Correct answer ratio and gain index (<g>) according to pre- and post-test results for two studies

	Item	Year 8 Students N = 125			Kalkan and Kiroglu (2007) study N = 100		
		Pre-test	Post-test	Gain	Pre-test	Post-test	Gain
		% correct			% correct		
1	Day-night cycle	9	91	0.80	91	93	0.22
2	Moon phases	30	55	0.36	23	30	0.09
3	Sun Earth distance scale	19	60	0.44	18	22	0.05
4	Altitude of midday Sun	8	56	0.53	29	39	0.14
5	Earth dimensions	12	57	0.44	5	14	0.09
6	Seasons	8	28	0.23	54	82	0.61
7	Relative distances	33	62	0.49	46	71	0.46
8	Moon's revolution	27	82	0.72	49	60	0.22
9	Sun's revolution	60	85	0.70	61	77	0.41
10	Solar eclipse	18	41	0.32	26	42	0.22
11	Moon's rotation	15	55	0.48	13	28	0.17
12	Centre of universe location	61	76	0.48	65	88	0.66
13	Seasons	38	89	0.81	67	88	0.64
		Mean		0.52	Mean		0.31

multiple choice questions, a gain index of 0.5 for an item indicates that for instance if 40% of students in the pre-test answered the question correctly, 70% answer correctly in the post test, being 0.5 of the possible gain from 40% to 100%. The mean gain reported by Kalkan and Kiroglu (2007, p. 17) was described as a "respectable 0.3". In contrast the mean gain for this study was significantly higher at 0.52. While the conditions may be different for the two groups, the comparison indicates a very strong gain in understanding of key astronomy concepts attributable to this guided inquiry approach.

In addition to these multiple choice questions there were extended challenges where students were encouraged to construct representations to respond to a question. In a reflection on the different ways in which the students responded to these open-response test questions the teachers commented:

> In their test answers if we gave them the space they would perhaps do a diagram to help with explanation or we might say use representation, they didn't just stick to the words [Jaz].

> And it was valued by those boys that do like to draw…the questions allowed them to represent their knowledge in multiple ways [Alice].

The students are not having to just write down a definition they are having to 'show' a definition through the use of representations [Kate].

7.7 Conclusions

Evidence from this study supports the claims made from our previous research (Tytler et al. 2013b) that a guided inquiry, representation construction approach leads to enhanced student outcomes and engagement with reasoning and ideas. The sequence has demonstrated that in this case of teaching astronomy:

- students have experienced enhanced learning outcomes, as evidenced by the results on the multiple choice test, by teacher perspectives, and by inspection of the quality of entries in students' journals; and
- the sequence resulted in sustained engagement with ideas, as evidenced both by teachers' assertions and again the quality and detail in students' journal entries, which were both detailed, and focused.

The astronomy sequence described in this chapter illustrates a number of aspects of our sociocultural theoretical perspective, described in the introduction, and provides insight into some of the positive outcomes of the approach.

We argue that the conceptual change challenges accompanying reasoning and learning astronomy, which fundamentally involve the capacity to accommodate the relationship between earth and space perspectives on sun-earth-moon relations, are fundamentally representational in character (Tytler and Prain 2013). As this astronomy sequence illustrates, the challenge involves learning to re-describe and coordinate a range of representations/models through which we visualise spatial relations.

On this matter, a key task in planning the unit with the teachers was identifying the key conceptual challenge: that of developing the representational resources that enabled students to model the relation between astronomical objects, and shift between earth and space perspectives. The figures illustrating student representational work illustrate the way this key challenge underpinned the tasks given throughout the unit. Even the plasticine modelling exercise involves the generation of an embodied sense of relative size and distance of the earth and moon. The rotate-revolve task also is a good illustration of how students were challenged to shift perspectives from their embodied sense of planetary movement to link with features of binary star or earth-moon relations. Most of the other figures were explicit examples of this challenge to coordinate representations of earth and space perspectives.

An important insight we have gained through our work, and that students are led to appreciate, is that any representation is inevitably partial, and fundamentally an approximation. We emphasise that 'fit for purpose' is an appropriate aim for representations that students generate, rather than 'correctness'. Thus, the discussion of what a globe represents (Fig. 7.1) emphasises the partial and selective nature of any representation. A map cannot fully represent the territory it purports to relate to. The varied and mostly insightful responses to the question concerning the difference between 'revolve' and 'rotate' (Fig. 7.6) illustrate the imaginative variation in representations that equally satisfy the challenge to articulate this abstraction. The multiple representations in students' journals (Fig. 7.8) illustrate how multiple representations are needed, including text, to satisfactorily solve problems and communicate explanations. Thus, the students' work illustrates this fundamental aspect of knowledge and reasoning in science.

The revolve-rotate sequence illustrates a further important construct that informs our work; that of the affordances of different representations and modes to support explanatory work (Prain and Tytler 2012). Thus, the role-play concerning the rotation of the moon focused students' attention on how the moon lined up at different points in its orbit, whereas the abstracted diagrammatic version (Fig. 7.3b) reifies this motion's temporal sequence to establish the spatial pattern. The movement from role-play to diagram, or between different diagrammatic perspectives, and text, illustrates the importance of representational re-description and coordination in problem solving and explanation in science.

An important aspect of this approach is the way in which formative and summative assessment is facilitated. In terms of formative assessment, students' representational work in journals, or in the public space, allows teachers to monitor and respond to their varied and shifting understanding. The approach where students are challenged to represent and discuss their representations publicly naturally involves ongoing interactions between the teacher and students concerning their ideas. Further, teachers have often expressed the view that students' drawn or modelled or embodied representations provide insights into their thinking that are sharper than tends to be achieved through text. This can be understood as an aspect of the affordance, as "productive constraint" (Prain and Tytler 2012), of modes, which forces specificity on student representational work that places demands on reasoning (for instance in Fig. 7.2 decisions needed to be made concerning relative size and position of the earth and sun, and placement of observers) and correspondingly exposes thinking for the teacher to respond to. In terms of summative assessment, we have found that designing post-tests with blank spaces where students are encouraged to represent multi modally can encourage high-level responses that allow judgements about depth of understanding. On the other hand, further research is needed concerning how such varied and complex responses such as those of Fig. 7.6 can be reliably assessed.

In interpreting the reasoning and learning that occurs as students make sense of their experience through the representations they are introduced to, or construct, we draw on Peirce's triadic model of meaning making (Fig. 7.9). The process by which students achieved an understanding of a solar eclipse for instance involves the construction of a representation of the sun-earth-observer system (Fig. 7.2) and the alignment of this with its referent, the experience of eclipses, in order to make meaning. Misunderstanding or partial understanding occurs when there is incomplete coordination of the representation with its referent, or between successive representations needing coordination for complex explanations. Reasoning is distributed across multiple modes, such as visuo/spatial, embodied, and verbal representations.

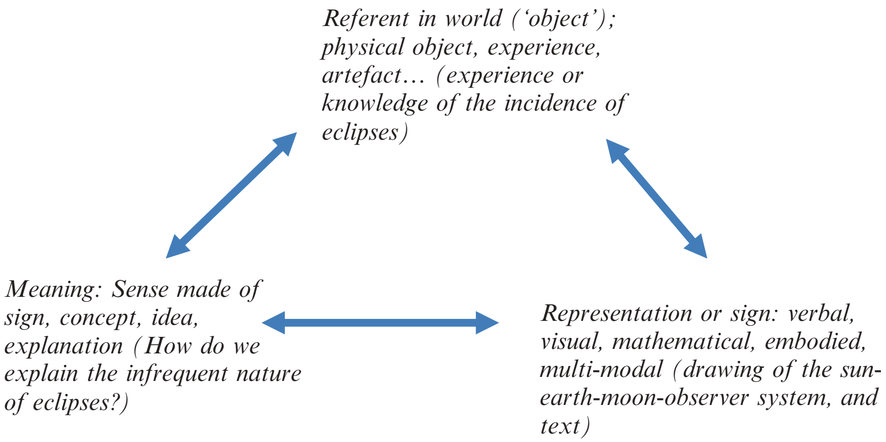


Fig. 7.9 Peirce's triadic model of meaning making

Thus, we argue that reasoning and learning inevitably involve representational work, and that representations are active mediators in the learning process, and a fundamental feature of the structure of knowledge. The development of a representational 'vocabulary' and the processes of creating and coordinating representations, are part of the process of induction into the disciplinary literacy of science. The astronomy sequence described in this chapter provides an illustration of how this can be effectively supported through a guided inquiry process

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Chapter 8
Learning About Forces Using Multiple Representations

Pasi Nieminen, Antti Savinainen, and Jouni Viiri

8.1 Introduction

This chapter focuses on learning about forces using multiple representations (MRs) and reports the results of four empirical studies conducted in Finnish upper secondary schools (Nieminen et al. 2010, 2012; Savinainen et al. 2013, 2017). First, the learning of forces and MRs are briefly described. Then, we present empirical studies in which students used and constructed various representations and discuss how this related to their learning of the concept of force.

8.1.1 The Concept of Force

The concept of force is central to physics education from primary school to university. In order to successfully apply the concept of force in physics, students must understand Newton's laws and related kinematics, such as position, velocity and acceleration. However, it has been found that the concept of force is not easy to learn and that students hold various alternative conceptions, which differ from the Newtonian concept of force (Duit 2009; Hestenes et al. 1992) because, for example, students commonly apply the 'dominance principle' or the 'impetus idea'. They tend to think, for instance, that in a collision of balls, the bigger ball dominates the collision and exerts greater force on the smaller ball. They also think that a moving ball has intrinsic force (i.e. 'impetus'). Both of these alternative conceptions conflict with the idea that forces arise due to interactions.

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8.1.2 Learning with Multiple Representations

The term 'representation' refers to something that stands for something else, and the term MRs refers to the use of more than one representation. Often, representations are categorised as either external or internal. External representations exist in the physical world (e.g. symbols and pictures) whereas internal representations concern knowledge and structure held in memory in different forms, such as propositions, productions, schemas and neural networks (see Opfermann et al. 2017, in this volume; Zhang 1997). In this chapter, we focus only on external representations in learning physics.

It has been empirically demonstrated that the use of MRs can help in solving physics problems (Rosengrant et al. 2009; Van Heuvelen and Zou 2001). MRs can be beneficial as they can act as visual aids and foster students' understanding of physics problems. In addition, they can build a bridge between verbal and mathematical representations and help students develop images that give mathematical symbols meaning (Van Heuvelen and Zou 2001). According to Ainsworth (2006), MRs have three different functions. First, they complement each other as they can express different information or support different processes. Second, MRs might help students understand a domain since one representation can constrain their interpretation of a second representation. Third, MRs can support the construction of deeper understanding as students integrate information from more than one representation. While MRs can be beneficial for learning, this does not mean that the proper use of MRs is easy for students. The representation used in a question affects students' performance (Dancy and Beichner 2006; Meltzer 2005). In addition, allowing students to choose which representation to use (a meta-representational skill) does not necessarily improve their performance (Kohl and Finkelstein 2005). Indeed, MRs can even impede learning as they may increase cognitive load (Ainsworth 2006).

One goal of physics education is that students learn to talk physics, which fundamentally demands the use of MRs. However, it can be difficult to learn to use them properly; therefore, their use deserves attention in teaching (Dufresne et al. 1997). For example, learning with a novel representation can be aided by also using a familiar, constraining representation (Ainsworth 2006). One implication for teaching is that students should learn to interpret, construct and move between different representations (Van Heuvelen and Zou 2001; Ainsworth 2006). Selecting the appropriate representations in a certain situation and designing one's own representations instead of relying on standard formats are among the meta-representational skills that scientists possess, and these should be learning goals in schools (diSessa 2004).

In this chapter, we focus on students' skills in using given representations (such as graphs, vectors, bar charts, motion maps and interaction diagrams), not their own. First, we discuss students' consistency in the use of MRs (i.e. representational consistency) in the context of forces. For this purpose, we use a test that we developed, the Representational Variant of the Force Concept Inventory (R-FCI). Second, we present results concerning the use of interaction diagrams (IDs) in the learning of forces.

8.2 Investigating Students' Representational Consistency in the Context of Forces

8.2.1 Participants and the Physics Course

Participants in our studies (Nieminen et al. 2010, 2012) were Finnish upper secondary school students (aged 16) who were taking their first and only mandatory upper secondary physics course which involves a minimum amount of algebra and includes a general introduction to physics, elementary kinematics, the force concept, Newton's laws, the energy concept, waves and radiation, the basics of matter, fundamental interactions and cosmology. Teaching time is approximately 30 lessons of 45 minutes each or 18 lessons of 75 minutes each, depending on the school's timetable. In this regard, the studies did not include a specific intervention for MRs, but MRs were used in the course. All students were taught by one of the authors, Antti Savinainen. The data were partly the same in both studies and they were collected from seven student groups during three academic years. In (Nieminen et al. 2010), the data ($n = 168$) were from students who answered all items of the R-FCI pre- and post-tests. In Nieminen et al. (Nieminen et al. 2012), students ($n = 131$) answered all items of the R-FCI and the FCI (see below) pre- and post-tests.

8.2.2 Representational Variant of the Force Concept Inventory

Students' understanding of the concept of force has been studied with multiple-choice tests (Bao et al. 2002; Hestenes and Wells 1992; Thornton and Sokoloff 1998). The most widely used test is the Force Concept Inventory (FCI) (Halloun et al. 1995; Hestenes et al. 1992). The FCI has 30 items that ask students to choose between Newtonian concepts and common-sense alternatives in various contexts (such as colliding cars and moving spaceships). Most FCI items relate to verbal representations, supplied with pictorial information. As we were interested in students' representational skills, we developed the R-FCI (Nieminen et al. 2010) for evaluation of students' representational consistency, which refers to the consistency of students' answers to isomorphic (in terms of content and context) multiple-choice items presented in different representations.

The R-FCI is based on nine items taken from the 1995 version of the FCI (Halloun et al. 1995): items 1, 4, 13, 17, 22, 24, 26, 28 and 30. Each FCI-item includes a verbal description of a physical situation with a question and five verbal multiple-choice alternatives, of which one is correct (Newtonian concept) and four are incorrect (common-sense alternatives). For the R-FCI, the original verbal multiple-choice alternatives of the FCI items were redesigned using various representations. For each of the nine FCI items, two new isomorphic variants (the same physical concept and context as similar as possible) were formulated in different representations (graphs, vectors, motion maps, bar charts). We use the term triplet to refer to three isomorphic items that consist of an original FCI item and two isomorphic variants. Altogether, there are nine triplets in the R-FCI, totalling 27 items (9x3) (see Table 8.1). The name of a triplet refers to an original FCI item. Triplet 4, for example, refers to FCI item 4, which addresses the forces between a car and a truck in a head-on collision. Figure 8.1 presents an example of a similar triplet as in triplet 4. (The real items of the R-FCI are not presented here in order to preserve the confidentiality of the original FCI item.) All the items of triplet 4 include a verbal description of the question to be answered. The description depends on the representation used; for example, in the vectorial item, names of vectors must be explained (see Fig. 8.1). The items of a triplet do not appear consecutively in the test booklet. For example, the items of triplet 4 are positioned in the test booklet as follows: 2nd, 11th and 20th item. All students answer all the items in the test booklet (which means that they answer all the triplets), and they are free to change their answers (they can move backward and forward between items).

The R-FCI items are based on the FCI, which is considered a reliable, valid test for evaluating understanding of the concept of force (e.g. Savinainen and Scott 2002). Data from 168 upper secondary students were used to evaluate the difficulty, discrimination and reliability of the R-FCI test. The averages of the item characteristic indices for difficulty, discrimination and item-test consistency were acceptable (Table 8.2). Two indices were calculated for the test as a whole. KR-20 indicated sufficient internal consistency and reliability, while Ferguson's delta revealed good discriminatory power (Nieminen et al. 2010).

8.2.3 Measuring Representational Consistency with the R-FCI

The R-FCI test can be used to evaluate students' representational consistency, that is, students' consistency in answering triplets of isomorphic items presented with different representations. (The same kind of idea has been expressed in the research

Table 8.1 Triplets of the representational variant of the Force Concept Inventory (R-FCI): Concept and representation of items

		R-FCI items				
Triplet	Concept	Verbal	Graphical	Vectorial	Motion map	Bar chart
Triplet 17	NI	x		x		x
Triplet 24	NI	x	x		x	
Triplet 22	NII	x	x		x	
Triplet 26	NII	x	x		x	
Triplet 4	NIII	x		x		x
Triplet 28	NIII	x		x		x
Triplet 1	Grav	x			x	x
Triplet 13	Grav	x	x	x		
Triplet 30	Grav	x		x		x

Note: NI = Newton's First Law, NII = Newton's Second Law, NIII = Newton's Third Law, Grav = Gravitation

Verbal
A large bowling ball collides head-on with a small pin. During the collision:

a) the ball exerts a greater amount of force on the pin than the pin exerts on the ball.

b) the pin exerts a greater amount of force on the ball than the ball exerts on the pin.

c) neither exerts a force on the other; the pin falls down simply because it gets in the way of the ball.

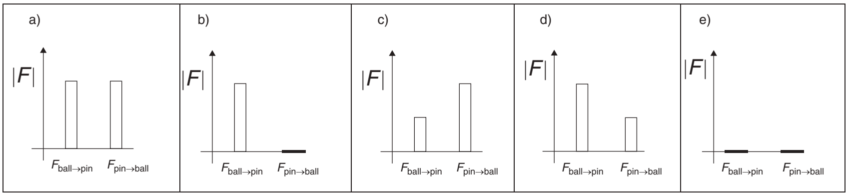
d) the ball exerts a force on the pin but the pin does not exert a force on the ball.

e) the ball exerts the same amount of force on the pin as the pin exerts on the ball.

Bar chart
A large bowling ball collides head-on with a small bowling pin.

The direction of the force exerted by the ball on the pin is positive. Let us denote the force exerted by the bow on the pin as $F_{ball\to pin}$ and the force exerted by the pin on the ball as $F_{pin\to ball}$.

Which of the following alternatives best describes the magnitude of the average forces |F| exerted on the ball and the pin during the collision?



Vectorial
A large ball collides head-on with a small pin.

Let us denote the force exerted by the ball on the pin as $F_{ball\to pin}$ and the force exerted by the pin on the ball as $F_{pin\to ball}$. Which of the following alternatives best describes the average forces exerted on the ball and the pin during the collision?

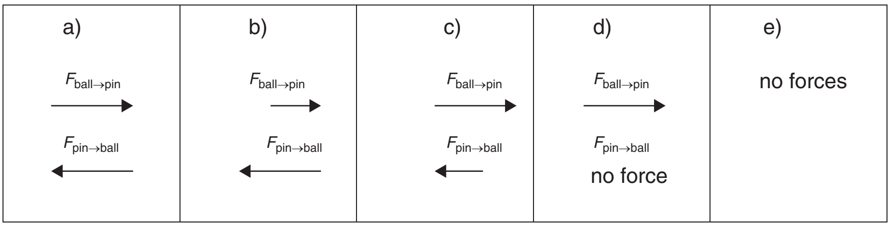


Fig. 8.1 Three isomorphic items in verbal, bar chart and vectorial representations

Table 8.2 Post-test item and test analysis of the Representational Variant of Force Concept Inventory (R-FCI)

Evaluation measure	Values of the R-FCI	Range	Desired values
Difficulty index	$M = 0.61$	0.08–0.97	0.3–0.9
Discrimination index	$M = 0.30$	0.05–0.65	≥ 0.30
Point biserial coeff	$M = 0.44$	0.15–0.69	≥ 0.20
KR-20	0.87	–	≥ 0.70
Ferguson's delta	0.97	–	≥ 0.90

Table 8.3 Representationally consistent answer patterns (shown in rows) for triplet 4 presented in Fig. 8.1

	Items			
Pattern	Verbal	Bar	Vectorial	Representational consistency
1	e	a	a	Scientifically consistent
2	a	d	c	Non-scientifically consistent
3	b	c	b	Non-scientifically consistent
4	c	e	e	Non-scientifically consistent
5	d	b	d	Non-scientifically consistent

literature using the notion of representational coherence (Savinainen and Viiri 2008)). The analysis must be done separately for each triplet, for which there are five possible answer patterns that are representationally consistent (shown in rows in Table 8.3). Thus, the student uses the same idea consistently when he or she answers items of a triplet posed in different representations. One of the patterns is scientifically consistent, which means that all answers are also correct. The other four patterns are representationally consistent, but the answers are incorrect (non-scientifically consistent). For example, in pattern 5 (d, b, d), after selecting alternative d in the verbal item shown in Fig. 8.1, the student might select the corresponding multiple-choice alternatives for the items in bar chart (b) and vectorial (d) representations. In that case, the student exhibits full representational consistency in the triplet, although the given answers are scientifically wrong.

One could argue that answering all the items correctly does not demonstrate representational consistency but only the correctness of student thinking. However, the incorrect alternatives in the test items (distractors derived from the FCI) represent common non-Newtonian concepts (such as the impetus or dominance principles), and they are very tempting from the student's perspective (Hestenes et al. 1992). In that regard, incorrect alternatives (misconceptions) are similarly relevant for students as is the correct alternative. Thus, it could be also argued that answering all the items non-scientifically consistently does not demonstrate representational consistency but only consistent non-Newtonian thinking. We note that it is virtually impossible to study pure representational consistency since some content (in our case Newtonian mechanics) must always be present. Thus, we think that representational consistency is a relevant and accurate concept here, as the representation is the most obvious variable between items of a triplet. Further, both correct and incorrect alternatives are important because they demonstrate more or less consistent Newtonian and non-Newtonian thinking.

Students' consistency in a given triplet was scored as follows:

- 2 points for selecting the corresponding alternatives in all 3 items of a triplet
- 1 point for selecting the corresponding alternatives for 2 of the 3 items of a triplet
- 0 points for selecting no corresponding alternatives for the items of a triplet

Table 8.4 shows examples of how to score the consistency for triplet 4 (Fig. 8.1). All nine triplets were scored, and the sum of the consistency scores for all the triplets is called the RC score.

8.2.4 Representational Consistency and Learning of Forces

In Nieminen et al. (2012), the R-FCI was used for measuring representational consistency as described previously. The FCI was used as a measure for students' conceptual understanding of forces. Further, we used the normalised gain on the FCI test for measuring the learning of forces (Table 8.5). The normalised gain was based

Table 8.4 Examples of scoring representational consistency (RC) for triplet 4 in Fig. 8.1

Student selection of the multiple-choice alternatives			
Verbal	Bar	Vectorial	RC score
e*	a*	a*	2
d	b	d	2
a#	a*	a*	1
d	b	a#*	1
a#	b#	a#*	0

Notes. *correct answer
not corresponding to the other item choices (see Fig. 8.1)

Table 8.5 The measures used for representational consistency and the understanding and learning of forces

Construct	Measure	Analysis
Representational consistency (RC)	RC score	This is based on the consistency of answer patterns within triplets of isomorphic items of the R-FCI. The RC score is the sum of the consistency points for all triplets.
Understanding of forces	FCI score	This is the number of correct answers on the FCI.
Learning of forces	FCI learning gain	This is ratio of actual gain to the maximum possible gain between FCI pre- and post-test.

Table 8.6 Spearman's rank correlation coefficients for different pre-test variables and FCI gain (n = 133)

Measure	1	2	3	4	5
1. Pre-test representational consistency	–				
2. Pre-test scientific consistency	.49	–			
3. Pre-test non-scientific consistency	.43	-.50	–		
4. FCI pre-test score	.47	.80		–	
5. FCI gain	.51[a]	.32[a]	.16	.33[a]	–

[a]$p < .001$. Spearman's rank correlation coefficient (ρ) was used because many of the variables studied did not distribute normally

on the students' pre- and post-test scores and defined (Hake 1998) as the ratio of the actual gain to the maximum possible gain according to the following formula:

$$G = \frac{Post - test\% - Pre - test\%}{100\% - Pre - test\%}$$

One could assume that high prior knowledge about forces would be related to high conceptual learning about forces, but previous studies have found that there is usually only a weak correlation between FCI pre-test score and FCI gain (Coletta and Phillips 2005; Hake 1998). In our study (Nieminen et al. 2012), this correlation was also weak ($\rho = .33$, $n = 133$; Table 8.6). Instead, we found a moderate, positive correlation ($\rho = .51$) between RC pre-test scores and FCI gain. Thus, students' representational consistency before instruction was more strongly related to their conceptual learning of forces than was their prior knowledge about forces.

However, it must be noticed that our definition of representational consistency contains both scientific and non-scientific consistency. The correlation between pre-test scientific consistency and FCI gain is .32 ($p < .001$), which is almost the same as the correlation between FCI pre-score and FCI gain. On the contrary, the correlation between pre-test non-scientific consistency and FCI gain is very weak ($\rho = .16$, $p = .063$). Thus, most of the correlation between pre-test representational consistency and FCI gain is due to the scientific consistency. However, it is still interesting that a non-scientific component even correlates with learning gain. Actually, it could be assumed that the correlation between pre-test non-scientific consistency and FCI gain should be negative as non-scientific consistency is related to non-Newtonian, common sense ideas. For example, according to Thornton (1995), consistent misconceptions are negatively related to conceptual learning. Table 8.7 shows that non-scientific consistency is the dominant component of the representational consistency in the pre-test, but it decreases during the course as students learn Newtonian thinking. Further, the correlation between post-test non-scientific consistency and FCI gain is moderate and negative ($\rho = -.55$, $p < .001$).

Table 8.7 Mean and standard deviation of students' representational consistency and its components' scientific and non-scientific consistency in the R-FCI pre- and post-tests

	Scientific consistency (%)	Non-scientific consistency (%)	Representational consistency (%)
Pre-test	17.68 (16.46)	46.61 (16.05)	64.29 (15.97)
Post-test	57.60 (20.91)	24.51 (14.39)	82.10 (13.28)

Note. Representational consistency is the sum of scientific and non-scientific consistency

8.2.5 Students' Performance Between Different Representations

In order to study the effect of the representation on students' performance, we compared students' (n = 168) correct answers between items within the triplets of the R-FCI pre- and post-tests (Nieminen et al. 2010). Figure 8.2 shows the percentages of correct answers in the triplets, with statistically significant differences between representations in pre- or post-tests. For example, for triplet 4 (Newton's III law) in the pre-test, the percentages of correct answers were 32% in the bar chart item, 26% in the verbal item and 26% in the vectorial item. When McNemar's tests were conducted, students were found to have performed better in the bar chart (p = .021) and verbal items (p = .049) than in the vectorial item. In the post-test, the differences between representations in the triplet 4 were no longer significant: 97% (bar chart), 96% (verbal) and 94% (vectorial). Table 8.8 shows all the statistically significant differences ($p < .05$) when the percentages of correct answers of the two representations of a triplet were compared using McNemar's test. There were more statistically significant comparisons in the pre-test (6) than in the post-test (3).

8.3 A Visual Representation Tool for Fostering Students' Ability to Construct Free-Body Diagrams and to Understand Newton's Third Law

In the preceding section, we discussed students' ability to interpret MRs (vectors, graphs, motion maps, bar charts, verbal descriptions) and how this ability is related to their learning of forces. In this section, we describe how a visual representation of interactions, an interaction diagram (ID), helps students' learning of forces. In both sections, students deal with given representation types, not their own creations. However, the ID representation discussed in this section is not a typical representation in teaching the force concept. In that regard, it is not a standard representation.

One important representation used in the teaching of forces is a free-body diagram (FBD), which is a combination of pictorial and vectorial representations that depicts force vectors acting on a target object. An FBD keeps track of all forces and their relative magnitudes and provides information about whether the object has

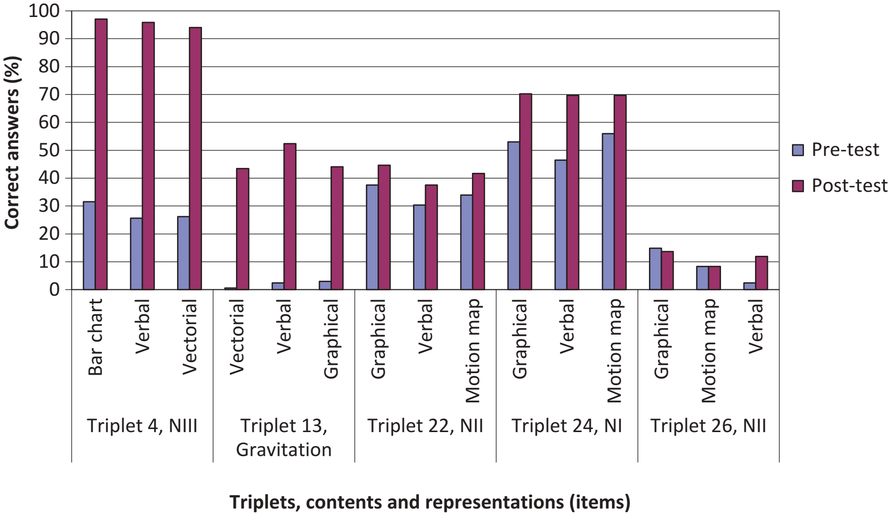


Fig. 8.2 The percentages of correct answers in the triplets, with statistically significant differences between representations in pre- or post-tests

Table 8.8 Statistically significant differences ($p < .05$) between correct answers of items (representations) in triplets

Triplet	Pre−/post-test	Compared representations	p-value
Triplet 4	Pre-test	BC vs. Ver	.021
		BC vs. Vec	.049
Triplet 13	Post-test	Vec vs. Ver	< .001
		Ver vs. G	.022
Triplet 22	Post-test	G vs. Ver	.017
Triplet 24	Pre-test	G vs. Ver	.035
		Ver vs. MM	.006
Triplet 26	Pre-test	G vs. Ver	< .001
		MM vs. Ver	.013

Notes. BC = bar chart, Ver = verbal, Vec = vectorial, G = graphical and MM = motion map. McNemar's test was used for the comparisons

acceleration, as the sum of forces is directly related to acceleration according to Newton's second law of motion. An object's motion can also be determined if information on velocity and acceleration is supplied (Reif 1995). It is unfortunate that students often have difficulties constructing correct FBDs, which are such powerful representations (McCarthy and Goldfinch 2010; Scherr and Redish 2005; Whiteley 1996). These difficulties with FBDs arise from the fact that many students struggle with the concept of force, even after instruction (e.g., Brookes and Etkina 2009; Halloun and Hestenes 1985; Hestenes et al. 1992).

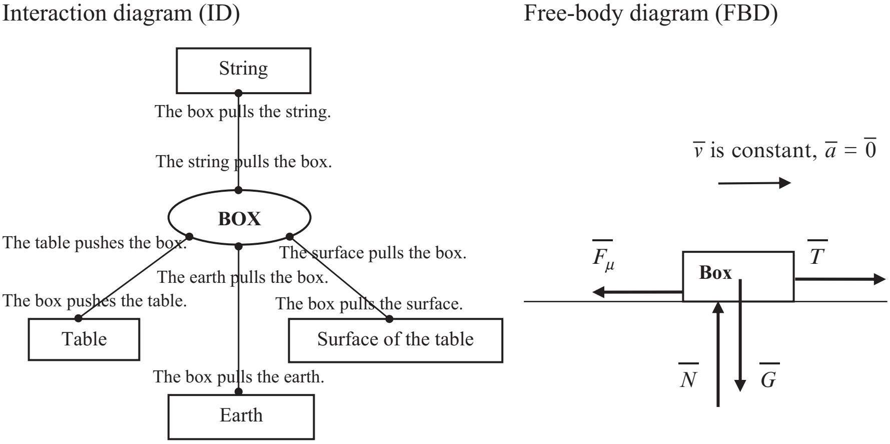


Fig. 8.3 The ID and the corresponding FBD of a box being pulled with a string along a table at constant velocity (Note: T = tension in the string, N = normal force, G = gravitational force and F_μ = frictional force)

A student cannot construct a correct FBD without correctly recognising what forces act on the target object: sometimes they miss a force or include extra force(s) (e.g., Whiteley 1996). Recognising the forces acting on the object might be easier if the teaching of the force concept is based on the idea of forces as interactions (Brown 1989; Hellingman 1989, 1992; Jiménez and Perales 2001; Reif 1995; Van Heuvelen 1991). One way to do this is to use a visual representation tool to visualise interactions between objects. Researchers have introduced various ways of visualising objects and the interactions between them: system schema (Hestenes 1997; Hinrichs 2005; Turner 2003), symbolic representations of interactions (Jiménez and Perales 2001; Savinainen et al. 2005), system-interaction diagrams (Tiberghien et al. 2009) and IDs (Hatakka et al. 2004; Savinainen et al. 2013), which we have used. Even though there are differences among these visualisations, they are similar representational tools since they each identify and represent interactions between objects, helping students perceive forces as the property of an interaction rather than as the property of an object.

The ID shows both the target object and the objects interacting with it (Fig. 8.3). There is a fundamental difference between an ID and a related FBD: The object's state of motion cannot be determined from an ID as it does not contain any information about the magnitudes of forces. Figure 8.3 shows examples of an ID and corresponding FBD, which represent a block being pulled with a string along a table at constant velocity.

The ID explicitly shows the interactions as pushes and pulls and, therefore, helps students to understand the connection between interactions and forces. The number of interaction lines in the ID corresponds with the number of forces in the FBD. Thus, students can see that there are no forces in the FBD without a corresponding interac-

1. Heavy use of ID groups

- The teachers were provided with ID-based intervention materials, including exercises on constructing FBDs, developed by the researchers.
- The teachers used a textbook (Hatakka et al., 2004) containing examples and exercises on IDs and FBDs, which support the intervention materials by providing additional practice on IDs and FBDs.

2. Light use of ID groups

- The teachers were not provided with the intervention materials.
- They used the same textbook containing examples and exercises on IDs and FBDs.

3. No use of ID groups

- The teachers were not provided with the intervention materials.
- They used a different textbook utilising FBDs teaching the forces in a standard manner without IDs (naturally, the no ID groups were not asked to construct any IDs).

Fig. 8.4 Characteristics of the three different groups

Table 8.9 Groups and students participating in the study ($n = 335$)

Group	Number of students
Heavy ID	75
Heavy ID 1	25
Heavy ID 2	27
Heavy ID 3	23
Light ID	57
Light ID 1	36
Light ID 2	21
No ID 1–6	203

tion. Consequently, using an ID helps students to draw only the correct forces in the FBD, with no extra forces (such as an impetus force along the direction of motion).

Some previous studies have shown that students' problem solving in the context of forces is improved when they are guided to first identify the relevant interactions and, from these, identify the forces (Heller and Reif 1984; Rosengrant et al. 2009). This result is understandable as, to solve quantitative problems in mechanics, students need to identify the forces acting on the body, construct a correct FBD and, based on it, formulate and solve the equation of motion. The ID might help students construct correct FBDs, so we studied the influence of using IDs on students' abilities to identify forces correctly, construct the correct FBDs and understand Newton's third law. We compared the learning results from the three different groups described in Fig. 8.4 (Savinainen et al. 2013).

The participants ($n = 335$, aged 16) of this study consisted of 11 groups of students (Table 8.9). Participating schools were differently sized from both cities and

Table 8.10 Questions on the IDs and FBDs for the heavy and light ID groups and timing when questions were administered during the course

Timing	Description of question	
	Context	State of motion
After teaching the ID and FBD	Parachute jumper going down	Uniform motion
	Cork floating on water	At rest
After completing teaching of the force concept	Book on a table	At rest
	Box lowered down by a rope	Uniform motion
	A girl in an elevator going down	Downward acceleration
As a part of the final exam	Ice hockey puck hit	Acceleration
	Ice hockey puck sliding	Deceleration
	Ice hockey puck on ice	At rest

Table 8.11 The classification of the quality of students' interaction diagrams

Excellent	Good	Poor
All interacting objects identified.	All interacting objects identified.	At least one interaction is missing or an extra interaction is included.
Interaction line or two-headed arrow presented.	Interaction line or two-headed arrow presented.	Or
Type of interaction (contact or distance) identified.	Type of interaction is not presented.	Forces are identified instead of interactions.
Or	And	Or
A written explanation of interactions is presented.	No written expression of the interactions is presented.	Diagram lacks essential features of an interaction diagram.

the countryside. Schools or students were not randomly selected for the study. Eleven teachers with more than 9 years of experience participated in the study. None were involved in the development of the intervention materials or the textbooks. Using the given materials and teaching their courses was their only participation in the research process. Data were gathered through questionnaires. Eight questions on IDs and FBDs (Table 8.10) were administered to the heavy and light ID groups. The questions were posed in different representations and addressed various physical situations and states of motion. Students answered the questions as ordinary learning tasks during the course. All the questions were derived from published literature, which lends some support to the validity of the contexts and framing of the questions (Savinainen et al. 2017). The reliability of the questions was checked using Cronbach's alpha. There were 16 total questions (eight IDs and eight corresponding FBDs): Cronbach's alpha for these questions was 0.841, which is an indication of good reliability (Mäkynen 2014, p. 140).

The no ID group answered the FBD questions at the end of the course, and all the groups answered questions on Newton's third law to test their understanding of it. The quality of students' drawn IDs were analysed based on whether they mentioned

Table 8.12 The classification of the quality of students' free-body diagrams

Excellent	Good	Poor
Forces are identified correctly.	Forces are identified correctly.	At least one force is missing or extra forces are included.
And	And	Or
Forces are presented as vectors.	Forces are presented as vectors.	The direction of the force vector is incorrect.
And	And	Or
Forces are properly labeled or named.	Forces are not labeled or named.	Lines are used instead of vectors or only a written explanation is used.
And	Or	Or
The vector sum of the forces is correct within 2 mm.	The vector sum of the forces is not correct within 2 mm.	FBD is otherwise unclear.

Table 8.13 Crosstab for the two FBD questions in the three groups. The number of student-drawn FBDs is reported in parenthesis

Groups	Quality of FBD		
	Poor FBD	Good FBD	Excellent FBD
Heavy ID	19.3% (26)	37.8% (51)	43.0% (58)
Light ID	51.5% (52)	15.8% (16)	32.7% (33)
No ID	62.0% (241)	22.9% (89)	15.2% (59)

Table 8.14 Averages of students' correct answers for the N3 law questions

Groups	*n*	Verbal open-ended (%)	Two verbal MCQ (%)	Vectorial MCQ (%)	Sum score (%)
Heavy ID	51	64 (46)	93 (17)	94 (24)	86 (16)
Light ID	24	23 (42)	56 (50)	71 (46)	52 (34)
No ID	186	15 (32)	62 (36)	31 (46)	42 (27)

Notes. Standard deviations are in parentheses. MCQ = multiple-choice question

relevant interactions and objects. The drawings were classified into three quality categories: excellent, good and poor (Table 8.11). Students' drawn FDBs were also classified based on whether they presented forces correctly (Table 8.12). For the interrater reliablity, two researchers analysed 10% of randomly selected students' IDs and FBDs. Cohen's Kappa was 0.958 for IDs and 0.855 for FBDs (Table 8.11).

We found that using IDs (Savinainen et al. 2013) improved the quality of FBDs and helped students identify forces when constructing FBDs (Table 8.13). The use of IDs also enhanced students' understanding of Newton's third law compared to the students who did not use IDs (Table 8.14; Savinainen et al. 2017).

8.4 Discussion and Conclusions

We have presented the R-FCI test, which can be used to evaluate students' representational consistency, something that other force concept tests cannot do to the same extent. We found that students' pre-instructional representational consistency (RC pre-score on the R-FCI) was more strongly related than their prior knowledge (FCI pre-test score) and conceptual learning of forces (FCI gain) to their conceptual learning of forces (FCI gain). The representational consistency, as we defined it, includes scientific and non-scientific answer patterns, which means that the student can answer representationally consistently regardless of the scientific correctness of the answer pattern. Most of the correlation between the RC pre-test score and FCI gain was due to scientific consistency. It is interesting that non-scientific pre-test consistency correlates even weakly with FCI gain as it is related to non-Newtonian, common-sense thinking. The correlation between post-test, non-scientific consistency and FCI gain is strongly negative, and students' conceptual understanding has been increased during the course. Thornton (1995) found that students who hold consistent non-scientific view were less likely to adopt scientific views than to hold inconsistent non-scientific views in the context of forces and motion. However, in Thornton's study, the consistency was related to the contexts of items, not to representations.

Our finding suggests that students' representational skills before instruction are related to their conceptual learning. Thus, it quantitatively supports the importance of MRs in learning. It is worth noting that our data are collected from one Finnish upper secondary school (as discussed below), and so replication studies would be valuable to confirm or reject this result.

The results show that students' performance varied among isomorphic items, which is in line with the findings of (Meltzer 2005) and Kohl and Finkelstein (2005). In our results, none of the representations were easier for students than the other representations. For example, a verbal representation was easier to understand than a graphical representation in Triplet 13 but harder in Triplet 22 (Fig. 8.2). It seems that the usability of a representation type depends on the context and content of a physical situation. It is also possible that, although different representations contain the same information about the given physical quality (e.g., the magnitude of force or velocity), students do not see the matter alike. Thus, one representation might trigger a misconception more easily than another. It must be noted that two items cannot be perfectly isomorphic. Therefore, it is not possible to know a definite reason behind differences in students' performance between isomorphic items, and this is one limitation of our studies and previous similar studies.

Another limitation in our studies (Nieminen et al. 2010, 2012) is that our data are not randomised and come from one course taught by one teacher. This weakens the generalisability of the results to other upper secondary school classes. As shown in Fig. 8.2, the rate of students' correct responses for the items of Triplet 4 (NIII law) is very high (94–97%). Similarly, students' achievement is very high in Triplet 28, which also focuses on Newton's third law. These very high results had an influence on the item and test evaluation measures. The difficulty indices of the items of Triplets 4 and 28 were too high (0.93–0.97), and the discrimination indices were very low (0.05–0.08). In comparison, students' achievement was found to be much lower in the study of (Jauhiainen et al. 2001) when they collected FCI post-test data (n = 386; aged 16–17) from 18 upper secondary schools around Finland. In their study, 61.4% of students answered FCI item 4 correctly (the verbal item of Triplet 4 of R-FCI), and 61.1% answered FCI item 28 correctly. Based on earlier research on Newton's third law, we think that the students' high performance on Newton's third law items in our studies is potentially due to the use of IDs but further analysis is needed to ascertain this relationship. On the other hand, keeping the teacher and the course constant brought consistency to our data and helped us to make interpretations within our data.

Some previous studies have shown that difficulties understanding Newton's third law can be overcome to a great extent with the use of a visual representation of the interactions (Hinrichs 2005; Savinainen et al. 2005). However, these studies had a weakness in that the researchers were the teachers during the implementation. In contrast, our study on IDs showed that the positive outcomes of these case studies could be replicated with teachers not involved with the research (Savinainen et al. 2017). From the representational point of view, our study also addressed the limitation of earlier studies that used only verbal representations to evaluate students' understanding of Newton's third law.

As explained earlier, our research design involved three kinds of groups depending on the degree to which IDs were utilised: heavy ID, light ID and no ID groups. We found that comprehension of Newton's third law was not higher in the light ID group (i.e., no intervention materials, only the textbook using IDs) than in the no ID group. This finding indicates that, when students were confronted with a textbook containing the idea of ID only, their learning did not necessarily improve. The intervention materials used in the heavy ID group informed teachers of how to introduce IDs and why they are useful in challenging students' preconceptions and supporting their learning. We did not provide extra training for teachers, but the short written instructions and teaching materials that were given evidently were enough for teachers to teach successfully using IDs. Thus, in addition to a textbook, a guide for the use of this representation, with examples that have been solved, should be provided if holding a training session is not a feasible option.

The success of using the ID approach can be explained by the idea of bridging representations (Savinainen et al. 2005). IDs function as bridging representations between a concrete physical situation and the more abstract vector representation of forces. Moreover, different representations contain different information and thus can complement each other (Ainsworth 2006). Therefore, it is better to use a combination of IDs and FDBs for the learning of forces rather than only FDBs. IDs clearly visualise interactions between objects and help students identify relevant forces. In this way, IDs helps override strong intuitions related to the dominance principle.

The learning benefit of combining different representations (i.e., IDs and FDBs) might arise from the ability of one representation to constrain the interpretation of a second representation (Ainsworth 2006). In our case, the ID constrains the interpretation or misinterpretation of the FDB (see Fig. 8.3). Using the ID, students do not forget relevant forces or invent extra forces, and thus they construct FBDs successfully. Furthermore, the two representations complement each other as the ID does not contain all the information present in the FBD; and vice versa, the FBD does not explicitly contain the information on interacting objects.

We found that the ID is a suitable learning tool, especially when interactions and forces are introduced at an upper secondary school level. More advanced students might cease constructing IDs as external representations but continue to use them as internal representations in their mental processing. Similarly, some students do not draw complete FBDs because they can mentally use FBDs (Kohl et al. 2007). If certain physical problems demand deeper elaboration, external IDs can be profitable, even for advanced students.

We conclude that the favourable learning outcomes of Newton's third law in the pilot studies (Hinrichs 2005; Savinainen et al. 2005), which were implemented by the researchers who also taught the classes, were replicated in the case of heavy ID group teachers who did not participate in the development of the teaching–learning sequence. However, the results suggest that the ID approach should be used systematically throughout teaching of the force concept in order to achieve enhanced understanding of Newton's third law. The light use of the ID approach or emphasising forces as interactions with no IDs had only a limited impact on students' understanding of Newton's third law. Overall, our study showed that the successful dissemination of evidence-based practise into physics classrooms is feasible without extensive teacher training.

Our studies contribute in many ways to the research on learning forces and multiple representations. We concur with previous studies that the learning of these subjects is far from easy. Nevertheless, our results suggest that students' representational skills are related to their conceptual learning of forces, and enhanced learning outcomes can be achieved with relevant representations such as IDs. Based on our studies, we are convinced that the appropriate use of MRs should be considered in textbooks, teaching materials, classroom activities and homework. However, the mere existence of relevant representations in textbooks is not enough because teachers do not necessarily understand the significance and purpose of novel representations. Thus, the importance of MRs must be stressed in preservice teacher education. In addition, it is worth noting that introducing a novel representation potentially increases students' cognitive load (Ainsworth 2006), and the students might not be able to reap the benefits of a new representation unless enough care is devoted to coordinating between the representations (in this case, IDs and FBDs). Nevertheless, our results show that an experienced teacher can adopt a novel representation in his teaching successfully, even without extensive training, but successful implementation requires the use of supportive materials besides a textbook.

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Chapter 9
The Conceptual Elements of Multiple Representations: A Study of Textbooks' Representations of Electric Current

Chee Leong Wong and Hye-Eun Chu

9.1 Introduction

Research findings showed that students did not always understand the role of multiple representations despite the efforts of a science teacher (Treagust et al. 2003). For instance, an argument offered in physics education for enhanced student understanding is to present physical concepts or problems using multiple representations in the form of words, diagrams, graphs, tables, or bar charts (Rosengrant et al. 2009; Van Heuvelen and Zou 2001). Moreover, the focus of representations could be on the use of animations, colour coding, icons, or simulations (Dancy and Beicher 2006; Homer and Plass 2010). Nevertheless, to promote active learning of students, physics teachers should use inquiry-related activities and analyse the elementary features of physical concepts which students may have difficulty in learning (Duit et al. 2012).

A framework of multiple representations of physical concepts could be succinctly based on Ainsworth's (1999) three main functions of multiple external representations: complementary information, constrain interpretation, and construct deeper understanding. Firstly, physics teachers should use representations that contain complementary information and support complementary cognitive processes. Secondly, there should be additional representations to constrain students' interpretation of an unfamiliar representation of a physical concept. Thirdly, multiple representations can be used to construct an abstract concept, and establish relations

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among representations such that there is a deeper understanding of a physical concept. However, the functions of multiple representations can be enhanced with a more structured approach in learning.

On the first function in providing complementary information, there could be at least three different levels of representation of concepts – macroscopic, symbolic (pictorial, algebraic, and physical forms such as graphs and analogies), and sub microscopic (Treagust et al. 2003). Additionally, in supporting complementary cognitive processes, there should be no gap in the sequence of representations. For example, the presentation of mathematical equations from PV/T = constant to $PV = nRT$ without including either $P \propto n$ or $V \propto n$ may cause a cognitive gap for students in learning (De Berg and Treagust 1993). However, physics teachers could plan a *deliberate gap* in the sequence of representations as an inquiry-related activity. Students could also be guided to identify gaps in the three different levels of representations, and they may have a more meaningful learning experience when they help each other to bridge the gaps between representations.

To have active learning and deeper understanding of physical concepts, the 'Educational Reconstruction approach' of Duit et al.'s (2012) can enhance the multiple representations framework of Ainsworth's (1999). Essentially, the framework of multiple representations could include two thinking and learning processes: elementarization and reconstruction. Firstly, the analysis of the conceptual *elements* of multiple representations can help to constrain interpretation. Secondly, students should *reconstruct* the physical concept in order to understand deeply the reasoning among its representations. In short, the constructivist conceptual change approach of Duit et al. (2012) can help to enhance the second and third functions of multiple representations.

Nevertheless, Ainsworth's multiple representations framework (Ainsworth 1999) does not necessarily help to define a physical concept and thus it does not always constrain interpretation. To constrain interpretation of physical concepts, we propose to include the following five conceptual elements of multiple representations: *object*, *nature*, *cause*, *mathematical equation*, and *condition* (Wong 2014). Furthermore, alternative conceptions of students could be related to these five conceptual elements (Wong et al. 2016). For instance, electric current is an important physical concept in which many students were found to have alternative conceptions (e.g. Duit 1985; Sanger and Greenbowe 2000; Tsai et al. 2007). In a study conducted by de Posada (1997), students were confused with three conceptual elements of electric current: *object*, *nature* and *cause*. Some students used the term 'atoms' (*object*) inaccurately, failed to convey the *nature* of electric current, and were unable to provide the correct *cause* of electric current. Thus, we should incorporate conceptual elements of multiple representations to constrain interpretation of a physical concept such that students' alternative conceptions could be significantly reduced.

In this chapter, we focus on five conceptual elements of multiple representations pertaining to electric current: *object*, *nature*, *cause*, *mathematical equation*, and *condition*. Utilising Duit and colleagues' theory of *educational reconstruction* (Duit et al. 2012), firstly, we discuss how physics teachers could analyse these conceptual elements of electric current and its representations – namely, elementarization – and secondly, we provide inquiry-related activities and suggest how students could be guided to reconstruct the concepts of electric current and its representations – namely reconstruction.

9.2 Elementarization (Analysing Five Conceptual Elements of Electric Current)

Based on our preliminary textbook analysis, five conceptual elements were identified as *object* (charge-carriers), *nature* (characteristics), *cause* (or effect), *mathematical equation*, and *circuit condition*. In this study, we analyse five conceptual elements of electric current that could be found in definitions and diagrams of 40 introductory physics textbooks. The selected textbooks were published in the United States (US) and United Kingdom (UK) because they are influential in the learning of students and teachers. We analysed definitions of electric current that are written in the form of "a rate of flow of charge" and diagrams that illustrate the definition within the same section of a textbook. These diagrams usually provided a definition of electric current or were labelled 'electric current'. The findings are summarised in Table 9.1 as shown below.

The concept of electric current was not expressed consistently in words and in diagrams among these textbooks. For example, the diagrams illustrating the concept of electric current are usually drawn as either Fig. 9.1 or Fig. 9.2 with varying

Table 9.1 Percentage of conceptual elements of electric current in definition and diagram of introductory physics textbooks (n = 40, percentage in parenthesis)

Conceptual elements	Examples of description or representation	Definition	Diagram
Objects / Charge carriers	Electric Charge (+ve and −ve) / Net charge	36 (90)	7 (18)
	Electrons (−ve)	2 (5)	7 (18)
	Positive charge (+ve)	0 (0)	5 (13)
Nature / characteristics	Rate of flow of electric charge	16 (40)	–
	Movement of charge / flow of electrons	20 (50)	19 (48)
	Conservation of electric current	–	2 (5)
Cause	Potential difference	1 (3)	3 (8)
	Electric field	1 (3)	4 (10)
Mathematical Equations	$I = dq/dt$ or $I = \Delta q/\Delta t$	26 (65)	1 (3)
	$I = q/t$	8 (20)	1 (3)
	Graph involving current, charge and time	–	4 (10)
Circuit Condition / Conduction Medium	Metal / Conductor / Wire	14 (35)	13 (33)
	Area / Surface / Point	10 (25)	5 (13)
	Complete Circuit	5 (13)	5 (13)

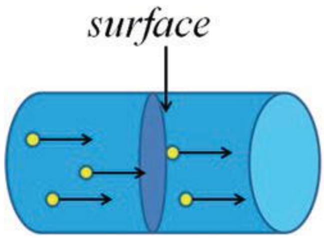


Fig. 9.1 Textbook A's diagram of electric current

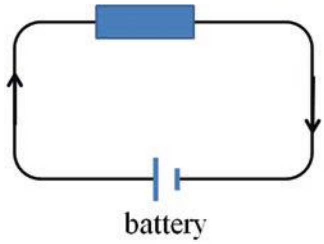


Fig. 9.2 Textbook B's diagram of electric current

details. They showed that electric current is a rate of flow of charge through a cross-sectional area (13%), metallic wire (33%), or in a complete circuit (13%) (See Table 9.1). Some textbook authors also specified charge carriers (object), conservation of electric current (nature), or electric field (cause) in the diagrams. In addition, the mathematical equation, $I = dq/dt$, could be illustrated graphically by relating electric current, electric charge, and time (10%).

Pertaining to the five conceptual elements, we first discuss possible alternative conceptions of students which can be related to problems of representations that are expressed in words, diagrams, or symbols, as found in current textbooks. Next, we provide suggestions how the concept of electric current can be presented verbally, diagrammatically, symbolically, and graphically for students in the secondary schools, colleges and universities.

9.2.1 Object

In a study conducted by Garnett and Treagust (1992), some students who studied both physics and chemistry had difficulty in understanding the concept of electric current as compared to students who only studied chemistry. For example, some dual-discipline students considered electric current as a flow of protons through metals or a flow of electrons through electrolytic solutions. Garnett and Treagust (1992) propose that the physics syllabus should adopt the electron flow model of electric current in metallic conductors. It is possible that different conventions of electric current used in chemistry and physics posed conceptual problems for some students. However, the problem of convention pertaining to electric current has not

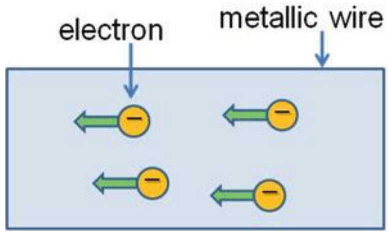


Fig. 9.3 Electric current as the flow of *electrons*

been resolved. For instance, Arons (1990) argues that the positive current convention[1] should be maintained in physics.

Among the textbooks, electric current was commonly defined as a flow of electric charge (90%) or electrons (5%). On the other hand, the diagrams that illustrate the definition of electric current specified the charge-carriers as electric charge (18%), electrons (18%), or positive charge (13%). Firstly, a better term for the *object* of electric current can be charged particles, charge-carriers, or electrons. The term electric charge should be used as an attribute of charge-carriers. Secondly, the charge-carriers could be specified as electric charge in a general definition of electric current, and they were drawn as electrons in a diagram as a specific definition. In other words, the verbal and diagrammatic representations of electric current may provide complementary information in the general and specific sense respectively, or vice versa.

As another example, a textbook definition of electric current could be specified as a flow of electric charge, but the diagram shows a complete circuit with a metallic wire and positive charge-carriers. In this case, the textbook author used the diagram to provide complementary information by showing a positive current convention. However, the charge-carriers in the metallic wire are electrons, and they are negatively charged. Thus, the flow of positive charge-carriers in the metallic wire is an idealization and it does not accurately represent the flow of charge-carriers in the real world.

In secondary schools, physics teachers should compare and contrast the two conventions of electric current with their students. When electric current is defined as a flow of electrons, it could be represented in Fig. 9.3 to show the positive current convention. The representations of electric current should be consistent diagrammatically, verbally, and symbolically. (The direction of electric current is symbolically represented by *I* with an arrow.) When electric current is defined as a rate of flow of charge-carriers, it could be diagrammatically represented as a flow of ions in electrolytes (Fig. 9.4). The charge-carriers as specified in the definition and its diagram should be complementary and consistent.

[1] Arons (1990) provides four reasons for maintaining the positive current convention in physics: (1) it underlies the definitions of electric field strength and potential difference; (2) the treatment of capacitive and inductive circuit elements; (3) the standard mnemonics of electromagnetism; and (4) the common notations in diagrams of electrical circuits.

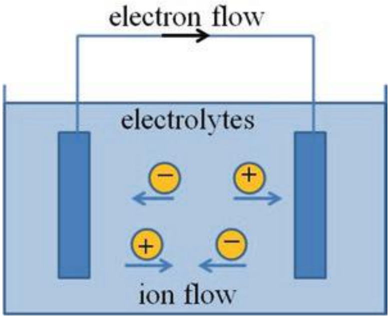


Fig. 9.4 Electric current as the flow of *ions*

At the college or university level, there could be more details in the Fig. 9.3 such as the copper atoms and the collision between an electron and a copper atom. It is possible that students still have misunderstandings of the figure that represent electric current in textbooks. For instance, electrons are sometimes drawn as balls of comparable size to the copper atoms (de Posada 1997). Physics teachers should explain that a representation of electric current may be idealised or exaggerated. An explanatory note could be included beside the figure to clarify the size of an electron and atom.

9.2.2 Nature (or Characteristics)

One common alternative conception of electric current is that it could be *used up* in an electrical circuit (Osborne 1983; Shipstone 1984). Students may have difficulty understanding the abstract nature of electric current or the idea of current conservation (Stocklmayer and Treagust 1996). On the contrary, students could be considered correct if they described the kinetic energy of electrons *being reduced* instead. This is because the speed of an electron may be reduced during collisions with the copper atoms in a metallic wire. Therefore, students are not completely incorrect when they conceptualised something is being used up in the electrical circuit. However, textbooks' definition of electric current does not specify a *constant* rate of flow of charge-carriers.

The nature of electric current was described in textbooks as either 'rate of flow of electric charge (40%) or 'movement of charge / flow of electrons' (50%). To be precise, physics textbooks written for secondary schools and colleges should include the phrase 'rate of flow' instead of simply 'flow'. That is, it should refer to the rate of flow of charge-carriers through a cross sectional area per unit time. However, the nature of electric current could be represented in diagrams as movement of charge / flow of electrons (48%) or conservation of electric current (5%). It should be noted that a diagram is a static form of representation and it mainly shows the direction of

Fig. 9.5 The constant *nature* of electric current

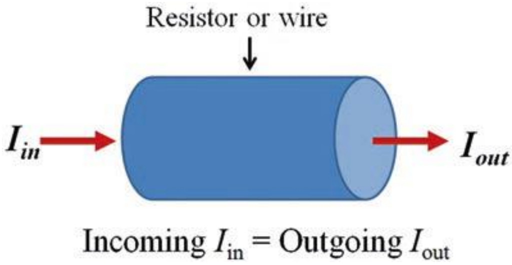
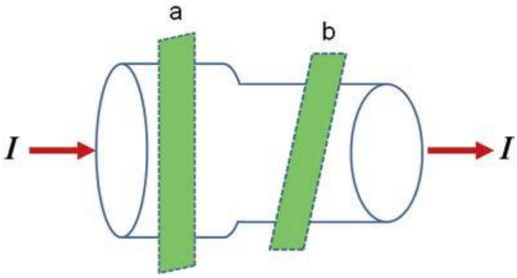


Fig. 9.6 *The current I* through the conductor has the same value at imaginary planes *a* and *b*



movement of charge-carriers. To show the rate of flow of charge-carriers, physics teachers should use an animation.

In secondary schools, the nature of electric current can be verbally represented as constant or conserved. Additionally, there could be a diagrammatic representation in which the incoming electric current before passing through a segment of wire (or resistor) is the same as the outgoing electric current after passing through the segment of wire (See Fig. 9.5). We should explain that a battery maintains the potential difference and electric current of an electrical circuit. Although an electron may slow down after a collision with the copper atom, it can gain back kinetic energy due to the presence of a potential difference. In other words, the flow of electrons is not constant from a sub microscopic perspective.

At the college or university level, the constant nature of electric current may be illustrated by a metallic conductor that has different cross-sectional areas (See Fig. 9.6). In short, the electric current has the same value through different *imaginary planes* that cut across a metallic conductor. However, the diagram may be considered as 'inconsistent' with a definition if it states that an electric current is the rate of flow of charge-carriers moving past *a point* per unit time. Essentially, the electric current through an imaginary plane or a point is an idealisation. In the real world, electrons may move haphazardly by colliding with the copper atoms in a metallic wire instead of travelling in a straight line as commonly shown in the diagrams of most textbooks. The random flow of charge-carriers could also be clearly illustrated by using an animation.

9.2.3 Cause

In de Posada's study, students were asked, "Why do metals conduct electric current? (Posada 1997, p. 453)" The common identified causes were coded as macroscopic and atomic. For macroscopic causes, students' responses included 'confluence', 'charge of battery', and 'temperature difference'. For atomic (sub-microscopic) causes, they could be 'atomic regularity', 'atomic movement', and 'atomic disorder'. Some students expressed that their difficulty in learning electric current is due to two different perspectives: macroscopic-energy (physics) and atomic world (chemistry). These students felt that the concept of electric current is inconsistently presented in chemistry and physics (de Posada 1997).

In general, the cause or effect of electric current is less explicitly specified in textbook definitions. Some definitions of electric current in physics textbooks included the following *cause*: potential difference (3%) or electric field (3%). For example, electric current in a metallic conductor is a flow of 'free' electrons due to a potential difference across the ends of the conductor (Breithaupt 2008). Similarly, diagrams of textbooks also include the same cause, potential difference (8%) and electric field (10%), when they are used to illustrate the definition of electric current. However, the term 'potential difference' may have different definitions when they are being used in different textbooks (Mulhal et al. 2001; Gunstone et al. 2009). It was reported that students were unable to clearly distinguish electric current and potential difference (McDermott and Shaffer 1992). Some students also interpreted *potential difference* as "possible difference" or "different ability" (Ryan 1985).

The term *potential difference* could still remain as a mysterious notion to many students (Dupin and Johsua 1987, 1989). It is an abstract concept which has not been adequately represented in many textbooks. In secondary schools, some physics textbooks provided diagrams such as "pressure difference causes the flow of water" to explain how the concept of a potential difference results in an electric current. Interestingly, only one physics textbook introduced the term *electric potential difference* to distinguish it from gravitational potential difference (Wilson et al. 2007). The term potential difference by itself is imprecise, and thus it can be misleading to students.

It has been reported that high school students had the alternative conception in which electric current results in electric potential difference rather than vice versa (Cohen et al. 1983; Dupin and Joshua 1987). Thus, physics teachers should distinguish the *cause* and *effect* of electric current. We may diagrammatically represent electric current in terms of cause and effect as shown below with short explanatory notes (See Figs. 9.7 and 9.8). The cause of electric current can be specified as an electric field or electrical potential difference, and the effect of electric current can be specified as a magnetic field. However, the concepts of electrical potential difference, electric field, and magnetic field are abstract and they should be clarified by using more verbal explanations.

In college textbooks, the *cause* of electric current can be more comprehensively specified as an electrical potential difference V volts supplied by a battery, and

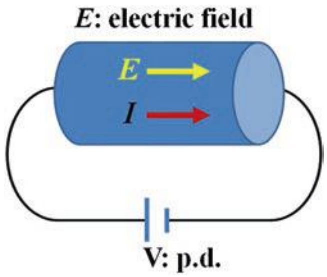


Fig. 9.7 The *cause* of electric current: electric potential difference or electric field

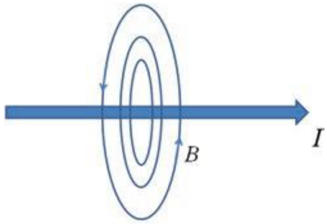


Fig. 9.8 The *effect* of electric current: magnetic field

sub-microscopically the *cause* is the electric field E in the metallic wire (Rehfuss 2004). Furthermore, electric current can be operationally defined and it is measurable by its *effect*. When electric current and magnetic field are represented in a diagram, some textbooks had shown only a circular magnetic field line or three equally spaced magnetic field lines around the wire. Generally speaking, the magnetic field strength of electric current can be illustrated by different spacing of the magnetic field lines (See Fig. 9.8). The spacing between the circular magnetic field lines is wider when it is further away from the electric current. This convention of drawing magnetic field strength can be related to the closeness of magnetic field lines about a bar magnet (Hewitt 2006).

9.2.4 Mathematical Equation

A physical concept is sometimes quantitatively represented by a mathematical definition or equation. However, it is possible to have an inaccurate understanding of the equation. The form of the equation could be represented with a diagram and its symbols should be clearly defined or explained. For example, the symbol I is used to represent electric current for historical reasons; Ampère (1822) used the symbol i to represent the *electric current intensity.*[2] Also importantly, the form of an equation whether it is written as $I = V/R$ or $V = IR$ may suggest different meanings. It is possible that students misinterpreted the equation if it is written as $V = IR$. This

[2] It is based on the French word *intensité*. Historically, André-Marie Ampère used the symbol i in formulating the eponymous Ampère's force law.

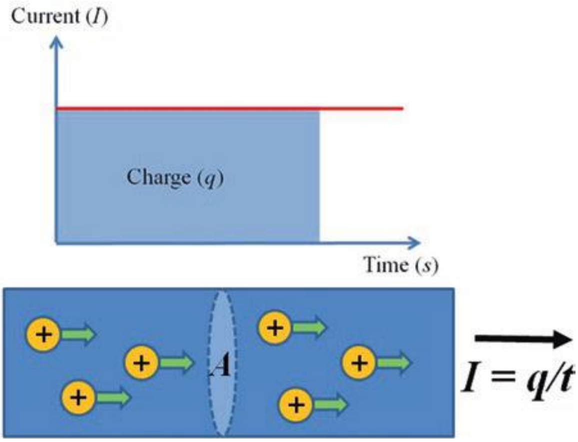


Fig. 9.9 Representing $I = q / t$

equation may suggest that voltage is a consequence of an electric current because students commonly conceptualise voltage as an attribute of an electric current (Afra et al. 2009; Cohen et al. 1983; Psillos et al. 1988).

The mathematical definition of electric current was stated as $I = dq/dt$, $I = \Delta q/\Delta t$ (65%), or $I = q/t$ (20%) among the textbooks. If the equation is $I = dq/dt$, it means an instantaneous rate of flow of charge-carriers. If the equation is $I = q/t$, it means an average rate of flow of charge-carriers. Two textbooks included both equations, $I = dq/dt$ and $I = q/t$, and explain that they are applicable to electric current that is changing or steady respectively. Similarly, the equation in the diagrams could be specified as $I = dq/dt$ (3%) or $I = q/t$ (3%). Textbook authors may consider it redundant to state the same equation in both definition and diagram. Alternatively, 10% of textbooks relate electric current, electric charge, and time by using a graph. One textbook states that the gradient of tangent line (dq/dt) of 'electric charge-time graph' is the electric current (Adams and Allday 2000). However, when a symbol such as q is not clearly defined pertaining to the graph, it can cause a cognitive gap in learning.

In short, the equation $I = q/t$ is related to the *nature* of electric current and $I = V/R$ is related to the *cause* of electric current. In secondary schools, physics teachers can represent the equation $I = q/t$ with a definition, a diagram, and a graph as shown in Fig. 9.9. Verbally, we can provide a definition such as "electric current (I) is the rate of flow of net charge (q) through a cross-sectional area of a wire per unit time (t)". This definition also provides the meaning of the symbols, I, q and t, used in the equation. In addition, students should be able to relate the mathematical definition of electric current, $I = q/t$, to a graph. For example, in an 'electric current-time graph', the area under the *curve* is the 'flowing electric charge', q. To be precise, the symbol q can be defined as the total amount of electric charge that flows through a cross-sectional area of a metallic wire within a time period, t.

In secondary schools, we propose physics teachers to represent the equation $I = V/R$ verbally and diagrammatically in Fig. 9.10. We can explain that *electric current* (I) *in a resistor with electrical resistance* (R) *is due to the potential difference* (V) *of*

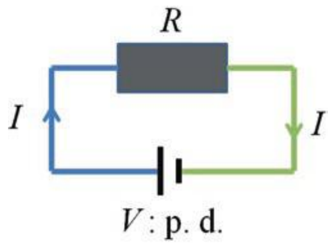


Fig. 9.10 Representing $I = V / R$

a battery. We should be aware of a limitation of this representation: what were drawn in the Fig. 9.10 are the wire, battery, and resistor. It is not always straightforward for students to conceptualise an *electric current* that flows in a wire, *potential difference* of a battery, and *electrical resistance* of the resistor. However, we can explain the concepts by using two colours in drawing the wire: any point in the blue segment has the same electric potential and any point in the green segment also has the same electric potential. If the battery has a potential difference of 1.5 volts, any point in the blue segment is higher than any point in the green segment by 1.5 volts. Thus, the electric current, I, through the resistor with electrical resistance, R, can be calculated by using the equation, $I = V/R$, if the resistance R remains constant. Physics teachers should explain that there is an idealisation in this figure in which the metallic wire has no electrical resistance.

At the college and university level, physics teachers should consider using the equation $I = \Delta V/R$ instead of $I = V/R$. This is because students might associate V with voltage or electric potential instead of potential difference. Therefore, it is important to emphasise the form of the equation for electric current as $I = \Delta V/R$ by comparing it with $V = IR$ and $I = V/R$. Furthermore, physics teachers should introduce the equation $I = dq/dt$ instead of $I = q/t$ for students who have some knowledge of calculus. However, some textbook authors may essentially state that "For constant electric current: $I = q/t$. For variable current: $I = dq/dt$". This may cause confusion to students because it does not seem consistent with the earlier notion of electric current which is conserved or constant. Physics teachers should explain that the equation $I = dq/dt$ is more precise than $I = q/t$ and it is applicable to constant electric current and variable electric current. In other words, electric current defined in terms of the equation $I = dq/dt$ may still be constant under ideal circuit conditions.

9.2.5 Condition

Circuit condition is an important consideration in determining electric current of an electrical circuit. In a study conducted by Dupin and Johsua (1987), they identified alternative conceptions of electric current in the contexts of circuit conditions. For example, some students had the alternative conception that an electric current could present in an open circuit. It was also reported that some elementary and middle

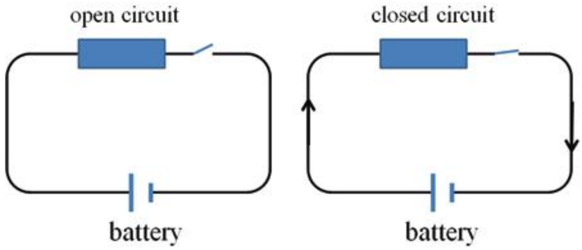


Fig. 9.11 open circuit / closed circuit

school teachers did not know how long a copper wire has to be such that there is a measurable effect on the electric current (Heller and Finley 1992). Physics teachers should explain that the electrical resistance of a copper wire may vary with the electrical potential difference of a battery. The electrical resistance of a copper wire can increase due to a heating effect of electric current, and depends on the temperature of the copper wire. Strictly speaking, the copper wire is not an ohmic conductor in which the ratio of electric current to its electrical potential difference remains constant, irrespective of applied voltage.

Many textbook authors do not explicitly specify any condition for the concept of electric current. Some textbook definitions specified circuit *condition* such as 'metal, conductor, wire' (35%), 'area, surface, point' (25%), or simply circuit (13%). In addition, the diagrams showed circuit condition such as 'metal, conductor, wire' (33%), 'area, surface, point' (13%), and a complete circuit (13%). Alternatively, a textbook states that "under the steady-state conditions assumed here, an electron must pass through plane *aa* for every electron that passes through plane *cc*" (Halliday et al. 2005, p. 684). Physics teachers should clarify that when an electric current is not constant, it can result in an induced electromotive force. Thus, when a switch is closed to form a complete circuit, it will take a short while for the electric current to reach a steady state or constant value.

In secondary schools, physics teachers may emphasise a simple circuit *condition* for electric current: closed circuit. We may compare a closed circuit and open circuit by using a Fig. 9.11. It shows that there is no electric current when the circuit is open, and vice versa. However, it has been reported that students could have different definitions of a complete circuit or closed circuit (Fredette and Lockhead 1980). Thus, we can define a complete circuit (or closed circuit) as a condition in which there is a continuous conducting path for an electric current to flow through an electrical circuit. Nevertheless, there is a limitation of diagrams in textbooks and in Fig. 9.11: it does not show how an electric current reaches a steady state in a complete circuit. If time permits, there should be an animation to show the flow of charge-carriers in reaching the steady-state condition, and there could be a graph to show how the average speed of charge-carriers varies with time.

In colleges or universities, physics teachers should explain that the constant nature of electric current is subjected to the conditions of circuit elements such as a copper wire. We can specify three circuit conditions as follows: (1) low constant

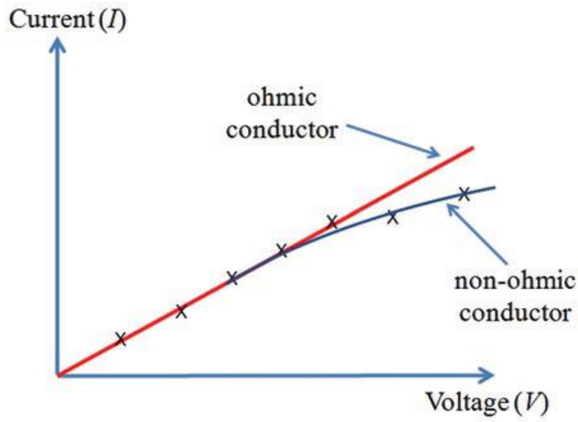


Fig. 9.12 current-voltage characteristic of ohmic and non-ohmic conductor

voltage; (2) constant temperature; and (3) constant size. If the potential difference across a copper wire is relatively high, there will be a heating effect and its electrical resistance can be significantly increased. Thus, the electric current through the copper wire can have a lower expected value depending on its temperature. In other words, the copper wire can behave like a non-ohmic conductor rather than an ohmic conductor, at a higher applied voltage. Experimentally, the ratio of an electric current to potential difference of a non-ohmic conductor can remain constant at a lower applied voltage (See Fig. 9.12). The current-voltage characteristic of an ohmic conductor is a straight line graph in contrast to a curve for non-ohmic conductor. Thus, the electric current through the copper wire does not always remain constant.

Generally speaking, the conditions pertaining to electric current may not be consistently expressed in words, diagrams, equations, and graphs. Students' problem solving skills on questions related to electric current could be weakened by the inconsistent representations of electrical resistance of a metallic wire. For example, in determining the electric current in a simple circuit, students should idealise the metallic wire as having *no* electrical resistance (as compared to a filament). In analysing the current-voltage characteristic of a metallic wire in a graph, students are expected to idealise the metallic wire as an ohmic conductor which has a constant electrical resistance. In answering a qualitative question, students may need to explain that the metallic wire is a non-ohmic conductor in the real world, and thus the electric current is not necessarily constant. The concept of electric current in relating to the metallic wire may vary depending on the context.

To summarise, textbook authors should improve the use of multiple representations of electric current effectively. The concept of electric current is multifaceted and may not be comprehensively presented among the textbooks pertaining to the five conceptual elements. In fact, each conceptual element may not be consistently presented in words, diagram, equation, and graph, among the textbooks or even within a textbook. In addition, the concept of electric current presented is usually idealised and does not accurately reflect the real world. Fundamentally speaking, there are problems of representations in which a diagram, for example, only provides a limited perspective of the concept of electric current. To provide a dynamic aspect of electric current, physics teachers should use animations to help students in visualising the concept.

9.3 Reconstruction

Students should be guided to reconstruct multiple representations of electric current. The concept of electric current can be unpacked as five conceptual elements as shown in Table 9.2. These conceptual elements of electric current are closely related and can be individually represented in a separate diagram or combined together with varying details as complementary information. Some suggestions on how to reconstruct the concept of electric current are presented as follows.

9.3.1 Reconstructing the Concept of Electric Current: Inquiry-Based Representation

Physics teachers should design an *inquiry-based representation* which can trigger students to think about a physical concept (Fig. 9.13). Students may be asked to explain which part of the electrical circuit has a higher electric current or whether the electric current is constant throughout the circuit. There could be discussion questions focusing on each conceptual element as shown below:

1. Object/charge carriers: What are the charge-carriers in an electrolyte? What are the charge- carriers in a copper wire? Why are there free electrons in a metal?

Table 9.2 Five conceptual elements of electric current

Conceptual element	Electric current
Object	Electrons Charge-carriers (positive)
Nature (or characteristic)	Conserved or constant
Cause (or effect)	Potential difference, electric field (cause) Magnetic field, heat (effect)
Mathematical equation	$I = V/R$ or $I = \Delta V / R$ $I = Q/t$ or $I = dQ/dt$
Condition	Closed circuit (or complete circuit)
	Circuit condition:
	(1) Low constant voltage
	(2) Constant temperature
	(3) Constant size

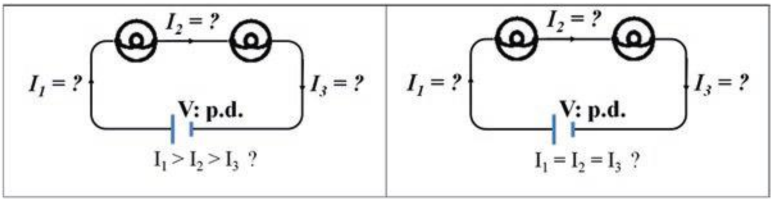


Fig. 9.13 An inquiry-based representation

2. Nature/characteristics: What is used up or reduced in an electrical circuit? Would you define electric current as a *constant* flow of charge? Is the constant nature of electric current an idealisation? Why?
3. Cause: Why do metals conduct electric current? How does an electron lose or gain kinetic energy in a copper wire or electrical circuit?
4. Mathematical equation: How do you determine the electric current in this electrical circuit? By using $I = q/t$? Or $I = V/R$?
5. Circuit Condition: What are the conditions for the use of this mathematical equation? What are the conditions for the constant flow of charge-carriers?

As a result of students' discussions and physics teachers' interventions, students should have a deeper understanding of electric current whether it attenuates after passing through a light bulb.

In this thinking activity, students could be requested to present their knowledge of electric current in words, diagram and mathematical equation. It is possible that students' multiple representations of electric current are inconsistent with each other. For example, their definitions and drawings pertaining to the *object* of electric current could be inconsistent. Students may also recall the concept of electric current as presented by a textbook which is inconsistent in multiple representations. Physics teachers can later use Fig. 9.3 to Fig. 9.12 to guide students to conceptualise the constant nature of electric current verbally, diagrammatically, and mathematically.

9.3.2 Reconstructing the Graphs of Electric Current

In his Nobel lecture, Wilczek (2004) mentioned that 'Ohm's first law is $V = IR$. Ohm's second law is $I = V/R$. I'll leave it to you to reconstruct Ohm's third law (p. 413)'. He clarified that different forms of the equation can suggest different meanings. Historically, there were also two versions of Ohm's Law: 'the law for a part of a circuit' and 'the law for a whole circuit' (Ashford and Kempson 1908; Kipnis 2009). The law for a part of a circuit is 'electric current through a conductor is directly proportional to potential difference at its ends, and the resistance of the conductor is constant'. The law for a whole circuit is 'electric current through a

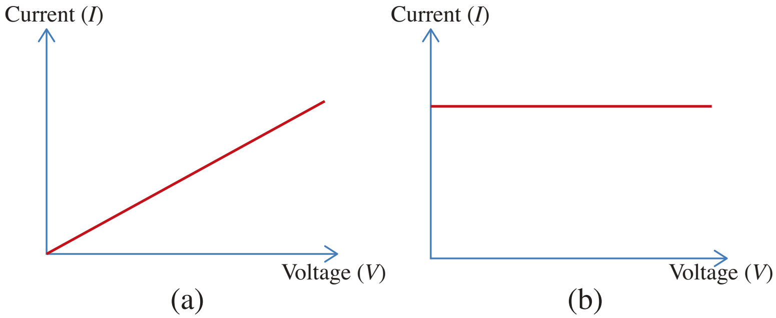


Fig. 9.14 Graph of electric current versus voltage

conductor is directly proportional to the potential difference at its ends and inversely proportional to its resistance'. These two laws could be represented by the following two equations respectively: $I = \Delta V/R$ and $I = E/(R + r)$. (E is the electromotive force of a battery and r is the internal resistance of the battery.)

Generally speaking, students tend to apply a mathematical algorithm or write down several possible equations, in order to analyse an electrical circuit. It is possible that they do not clearly understand the reasoning behind Ohm's law and its equation. Thus, students may be asked to explain which of the following graphs (electric current versus voltage) below correctly represents Ohm's law (Fig. 9.14). Similarly, students should be requested to justify their answers in words, diagram (submicroscopic and macroscopic perspective), and mathematical equation.[3]

Importantly, multiple representations cannot replace the experiment in which students interact with the equipment in the laboratory. There should be an experiment for students to reconstruct Ohm's law in order to understand the operational meaning of electric current, potential difference and electric resistance in the real world. During the experiment, potential difference is the manipulated (independent) variable and electric current is the measured (dependent) variable. In a current-voltage graph, the x-axis represents the potential difference and y-axis represents the electric current. The *correct* graph is a straight line which passes through the origin (Young and Freedman 2004). It can be represented as $I \propto \Delta V$ which means that the electric current through the electrical circuit is directly proportional to the potential difference of an ideal battery. However, students and teachers may not fully understand the concept of direct proportionality which is embedded in the equation (Yap 1992).

We should also let students analyse the electric charge-time graph (See Fig. 9.15). There could be discussion questions such as "which of the following graph is correct?", "what is the meaning of gradient of electric charge-time graph?", "could

[3] Historically, Ohm used the equation $x = a/(b + l)$ to model his experimental data. In universities, Ohm's Law may be symbolically represented as $J = \sigma E$, where $\boldsymbol{J}$ is the current density at a given location in a conductor, $\boldsymbol{E}$ is the electric field at that location, and σ is the conductivity of a material.

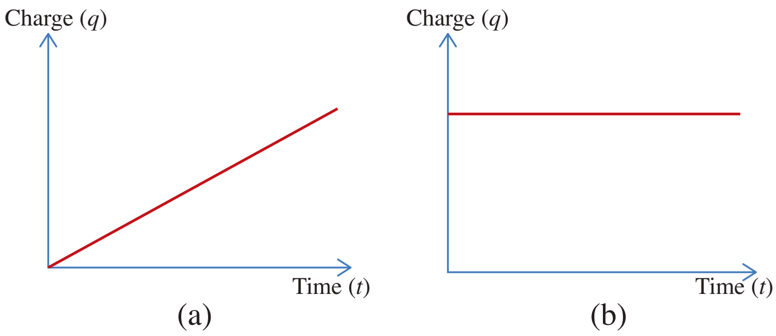


Fig. 9.15 Graph of electric charge versus time

electric current be deduced by using the equation, $I = q/t$ *or* $I = dq/dt$?", "what is the meaning of the symbol q?", "does q means total charge, net charge, an amount of charge?", "should the symbol Δq be used instead?" However, a textbook simply termed q and Δq as 'charge flowing' (Dobson et al. 2002). We can explain that the symbol Δq refers to a very small amount of electric charge that flows through a cross-sectional area during a very short time interval, Δt.

9.3.3 Reconstruct the Concept of Electric Current: Macroscopic and Sub-microscopic Perspectives

During a revision period, physics teachers could ask students to summarise the concept of electric current from the macroscopic and sub-microscopic perspectives. (Students may imagine that they take over the role of a physics lecturer.) As an example, the macroscopic and sub-microscopic perspectives of electric current can be represented by including four conceptual elements: *object*, *nature*, *cause*, and *condition.*

Macroscopic Perspective It is possible to have a macroscopic perspective of electric current with four conceptual elements as shown in Fig. 9.16. Physics teachers should guide students to provide four verbal explanations pertaining to this figure. Firstly, the *object* related to electric current may include a copper wire, resistor, and battery. Secondly, the *nature* of electric current is shown by two arrows with identical length in parallel to the wire. This suggests that the electric current remains constant after passing through a resistor. Thirdly, the macroscopic *cause* is the potential difference due to the presence of a battery. In other words, the battery maintains the potential difference and provides electrical energy for the constant flow of charge-carriers. Fourthly, the macroscopic *condition* may refer to a simple 'one loop' closed circuit. Because of this simple circuit condition without additional branches, there is no splitting of the electric current throughout the electrical circuit. Thus, the electric current is constant and having the same value everywhere in the copper wire.

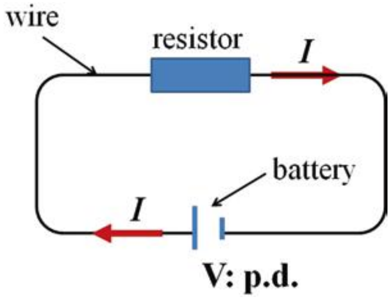


Fig. 9.16 A macroscopic perspective of electric current

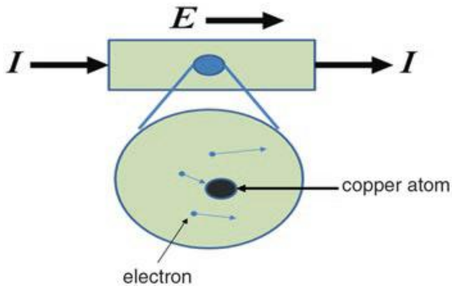


Fig. 9.17 A sub-microscopic view of electric current

Submicroscopic Perspective It is also possible to have a sub-microscopic perspective of electric current with four conceptual elements as shown below (Fig. 9.17). Firstly, the object may refer to copper atoms and electrons. Secondly, the individual electron is not moving in a perfectly horizontal direction from a sub-microscopic perspective. There is randomness in the flow of electrons with different velocities as shown in Fig. 9.17; the length of an arrow represents the speed of an electron. Thirdly, the sub-microscopic cause is an electric field due to the presence of a battery. The electric field is the cause that results in the electric force on the electron, and the electric current. Fourthly, the circuit condition may refer to a copper wire which has a relatively low electrical resistance. Sub-microscopically speaking, there will be a heating effect due to the electric current, and it can increase the random motion of the lattice atoms, as well as the collision rate (between an atom and electron), and thus increase the electrical resistance. Hence, the electric current may not remain constant under real circuit conditions.

Synthesising Five Conceptual Elements of Electric Current Electric current in a metallic conductor can be defined as a constant rate of flow of 'free' electrons due to a potential difference across the ends of the conductor, under constant circuit conditions. Initially, the concept of electric current can be presented with a comprehensive definition, and elaborated in greater detail as deemed appropriate by physics teachers. Subsequently, students could be guided to translate the conceptual elements of electric current in different representations. As a summary, both macro-

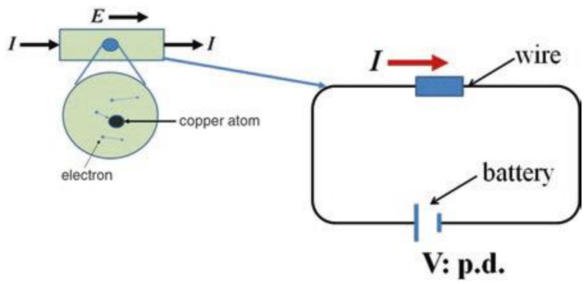


Fig. 9.18 A diagrammatic definition of electric current

scopic and sub-microscopic representations of electric current can be combined together as a 'diagrammatic definition' (Fig. 9.18). It provides a comprehensive representation of electric current diagrammatically. Based on this diagram, a student may explain that the electrons are moving past the *stationary* copper atoms due to an electric field. However, students should be guided to reconstruct the concept of electric current by providing a summary or designing their own diagrammatic definition.

Nevertheless, physicists may prefer a field model of electric current as compared to a fluid model (Stocklmayer and Treagust 1994). Thus, physics teachers could provide a brief historical development of the concept of electric current. By reconstructing the concept with a historical perspective, it may help students to distinguish an early scientist's conception of electric current with the current scientific concept. Better still, some historical drawings could be used for analysis during classroom learning.

9.4 Conclusions and Limitations

In addition to focussing on the different forms of representations, physics teachers should analyse the conceptual elements of these multiple representations because they were inconsistently represented in textbooks, and thus possibly contribute to students' alternative conceptions. For instance, the concept of electric current is multifaceted and it can be unpacked as involving the following elements: object, nature, cause, equation, and condition. These five conceptual elements of electric current should be consistently presented from the macroscopic and sub-microscopic perspectives to *constrain* students' interpretation. Moreover, a conceptual element may be *complementarily* presented via a hybrid of verbal, diagrammatical, symbolical, and graphical representations. Most important, students should be guided to *reconstruct* the physical concept for a meaningful and deeper understanding. Physics teachers may present other physical concepts by using multiple representations with these five conceptual elements in mind.

One limitation of this chapter is that we only analysed definitions of electric current that are essentially written as "a flow of charge". Most textbooks also included statements to the effect of 'a potential difference causes an electric current'. However, there could be disagreement whether this statement should be regarded as a definition. It depends on an educational researcher's definition of *definition*. Similarly, we only analysed diagrams that were used to illustrate a definition of electric current. For the purpose of focus, we did not include diagrams that appeared in another section which illustrated the notion of potential difference or how pressure difference causes a flow of water. These diagrams could be included in another study if a researcher adopts a broader definition of *definition*.

Another issue is that physics teachers could have difficulties in using multiple representations. In Yap's (1992) study, he assessed pre-service teachers' conceptions of direct proportionality in identifying a graph, providing a mathematical relationship, identifying the pattern in a table, and expressing the concept in words. No one in this study was consistently correct across all of the designed activities in different representations. Many participants simply defined direct proportionality as '*Y* increases as *X* increases', and they were inconsistent in providing the reason for the concept with respect to a graphical representation. Yap (1992) proposes a need in science teacher education to train preservice teachers and in-service teachers in integrating their knowledge from activities in different representations, thereby leading to a meaningful understanding. We should not assume physics teachers can master the use of multiple representations without difficulties.

Importantly, students and teachers should be warned of the problems of representations in physics. They should be shown the Belgian surrealist painter René ***Magritte's*** painting of a pipe which has an inscription 'this is not a pipe' (Gilbert and Treagust 2009). However, students and teachers may not immediately realise that 'this is only a *representation* of a pipe'. Some students could simply make sense of the painting by thinking that the word *pipe* has another definition such as a 'metal tube that is used to convey water, gas or oil'. Thus, it is not a 'narrow tube with a small bowl at one end for containing tobacco' as shown. It is possible that students make sense of the painting for other different reasons that were not intended by the painter. Similarly, students may not always understand the multiple representations of a physical concept despite the best efforts of a physics teacher.

Appendix A: Textbook References

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Part III
Multiple Representations: Focus On Reasoning and Representational Competence

David F. Treagust

The importance of reasoning in effective learning has been demonstrated with an increasing number of studies in a wide range of content domains. The four chapters in this Part add to that body of literature, often introducing ideas that have not been previously presented and do so within a range of physics topics from the university curriculum.

In Chap. 10, Mueller, Hettmannsperger, Scheid and Schnotz introduce two aspects of multiple representations, namely representational coherence ability (RCA) and the representation related conceptual change (RCC) in geometric optics. They demonstrate students' attainment of these terms in experiments called representational activity tasks (RATs) that involve two or more types of representations simultaneously and explicitly ask students to provide elaborations on their reasoning of the various connections between them. When merely addressed in an implicit way, as in usual learning tasks, this representational competence does not develop properly.

In Chap. 11, Kohl and Finkelstein describe a series of empirical studies on undergraduate students' use of representations in introductory physics – wave optics and atomic physics – in order to investigate when and how students use representations and to understand the impacts of varied instructional strategies on student reasoning and their ability to perform with different representations. Their research showed that student performance on isomorphic problems can vary, often dramatically, simply by changing the representational formats of the questions posed and that teaching environments that regularly use multiple representations and those that hold students responsible for using multiple representations positively impacted students' performance and ability to reason across representations.

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In Chap. 12, Yeo and Gilbert examine the nature of 'successful' students' representational capabilities when constructing explanations across four classes of phenomena in physics – dynamics, thermal physics and electromagnetic induction and superposition. Taking a case study approach, four representative and successful explanations produced by students in these topics were examined along three dimensions: function, form and level. Using multimodal analysis method, interpretive and causal explanations of one student were analysed over an extensive time period illustrating how these explanations mediated students' thinking and reasoning processes.

In Chap. 13, Sullivan and her colleagues investigated middle school student learning of physics principles related to the phenomena of global heat transport through the use of a virtual interactive textbook (VIT) that featured multiple representations including video, animations and a virtual experiment. Analysis of videotaped, collaborative student dyadic interactions and whole class discussions revealed how both students and teachers guided student interactions with the representations through the provision of conceptual, procedural, and metacognitive scaffolds and prompts to student thinking and learning activity. For example, students were able to meaningfully engage with the visualizations, scaffold one another's knowledge, and co-construct understandings from cross-referencing the various 3D and 2D depictions of the process of convection. Moreover, teachers used the pedagogical strategy of metacognitive prompting in their interactions with students around the visualizations.

Chapter 10
Representational Competence, Understanding of Experiments, Phenomena and Basic Concepts in Geometrical Optics: A Representational Approach

Andreas Müller, Rosa Hettmannsperger, Jochen Scheid, and Wolfgang Schnotz

10.1 Introduction

A considerable body of empirical and theoretical research has shown the essential role of multiple representations (MRs) for science learning, on the one hand for specific aspects such as conceptual learning (Nieminen et al. 2012; Tsui and Treagust 2013, ch. 2, 5, 16) and reasoning (Tytler et al. 2013, ch. 6; Verschaffel et al. 2010), or problem solving, transfer or communication, on the other hand for expertise in general (Gilbert and Treagust 2009, ch. 12; van Someren et al. 1998, ch. 2). A theoretical account of these findings is discussed in Chap. 1 of this book in terms of models for the cognitive ("dual coding" family of models) and educational (DeFT; Ainsworth 2006) aspects of MRs. On the epistemological level, the term 'representation' is understood as a tripartite relation of a referent Rt (or object),

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its representation Rn, and the meaning M (or interpretation) of Rt, Rn and of their interaction. This relation is referred to in various ways (eg. ‘Peircean triangle’, or ‘triangle of meaning’; see Tytler et al. 2013, ch. 6).

In the present contribution, we review the background and results of two connected studies of MRs related to experiments (Hettmannsperger et al. 2014; Hettmannsperger 2015; Scheid 2013; Scheid et al. 2014). We had chosen geometrical optics as area of investigation, because it is rich in MRs, and it is taught as one of the first subjects in many German physics curricula, so it seemed worthwhile to know if there are effective learning approaches already at that stage. The focus of investigations was on two aspects, which are considered to be essential for the learning of science in general, and of physics in particular.[1]

10.1.1 Experiments and Representational Coherence Ability

It is well known in science education, that proper understanding of and learning from experiments (or observations) requires mastery of a multiplicity of representational formats (RFs), from the “enactive” or “operational” manipulation of the experimental devices and materials (Bruner 1964; Piaget 1977) to the most abstract level of the mathematical formulation of the law(s) of nature underlying (or investigated) in a given experiment (Feynman 1990). An important consequence of the above-mentioned essential role of MRs for science (for many individual aspects and in general) is that RCA is not an isolated competence, to be distinguished from domain-specific expertise, but it is rather an integrative component of it (see Anzai 1991; van Heuvelen 1991). There is ample evidence for this crucial role of RCA especially also for experiments and observations, both from science education research (Gilbert and Treagust 2009; part II, 107 pp.; Tytler et al. 2013, in particular ch. 3, 6, 9) as well as from best practice (Marzano et al. 2001).

According to research syntheses by Höffner and Leutner (2007) and Ploetzner and Loewe (2012), the level of abstraction (or realism) is an essential feature of MRs, and we propose the idea of a “representational ladder” related to an experiment (and/or observation), see eg. Fig. 10.1 (the visual form was inspired by Leisen 1998) which is a kind of meta-representational metaphor and visualization: To use a ladder properly, one not only has to be able to stay safely on every rung, but also to easily climb up and down. In the example of Fig. 10.1, learners can do an image formation experiment or work with a photograph or realistic drawing of it according to the lowest line in the figure. The ray diagram encapsulates the optical situation in a schematic way, allowing, given the object position, to determine by geometrical construction the position and size of a sharp image. The mathematical equations in the topmost line allows to answer the same question in a purely symbolic way (its semi-quantitative textual formulation provides an intermediate step helping to interpret the quantities and the relationships in the equation). Note that Fig. 10.1 does merely propose a visualization (representation!) of different levels of abstraction, and is not a proposition of a learning progression.

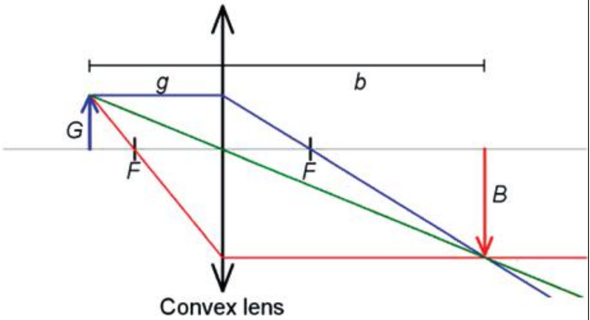
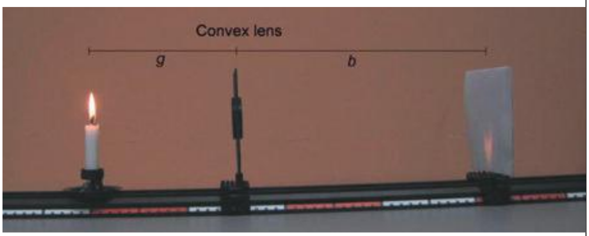
level of abstraction →		
	mathematical description	$\frac{B}{G}=\frac{b}{g}\ ;\ \frac{1}{f}=\frac{1}{g}+\frac{1}{b}$
	semi-quantitative description	The closer the object to the focus, the larger the image distance and size
	schematic drawing (ray diagram)	
	real(istic) drawing or photography	

Fig. 10.1 "Representational ladder" of a geometrical optics experiment

10.1.2 Experiments and Representation Related Conceptual Understanding and Change (RCU/C)[2]

A growing strand of research is focusing on the representational demands of developing students' conceptual understanding and change, pointing out that students need to develop and understand multiple representations to improve their understanding of basic scientific concepts (Botzer and Reiner 2005; Hubber et al. 2010; Plötzner and Spada 1998).

In particular, understanding the link between scientific experiments and their conceptual basis requires the learner to deal with multiple representations at different levels of abstraction, such as describing observed phenomena by oral or written language in terms of appropriate concepts, or expressing experimental results by schematic diagrams or mathematical relations containing formal representations of these concepts. In a qualitative study of student's representations in the domain of particle models about solids, liquids, and gases, Waldrip et al. (2010) showed that student-generated representations can foster students' conceptual learning, and what teaching features offer effective support for this.

Hubber et al. (2010) confirmed the efficacy of using multiple representations in mechanics while teaching and learning the concept of force in a qualitative video study. Borrowing from other fields of science education, the importance of MRs for conceptual learning has been underlined in biology (Tsui and Treagust 2013) and chemistry (Taber 2009), in particular for the fundamental topic of the micro-macro level connection (Cheng and Gilbert 2009), and also in geoscience (Sell et al. 2006). A classical example where a domain specific representation supposed to be a tool turns into an obstacle specific for the learning topic of this study, ray optics, is the idea that the image disappears, when the principal rays used for image construction are blocked (s. Goldberg and McDermott 1987).

Regarding conceptual learning from and about experiments, cognitive conflict with discrepant events has been discussed since long as a basis for conceptual understanding and change, both in the discipline (Thagard 1991), and for the individual (Thorley and Treagust 1987; Kim and Choi 2002; Lee et al. 2003; Başer 2006; Zimrot and Ashkenazy 2007). While the precise theoretical underpinnings of conceptual change are still under discussion, in particular with respect to the sometimes surprising persistence of misconceptions (Andersson and Kärrqvist 1983; Fetherstonhaugh and Treagust 1992; Langley et al. 1997; Heywood 2005), there is growing consensus that an essential element for conceptual learning is that learners deal actively with discrepant information, whether experimental or other, i.e. that learners need to use their own cognitive and representational resources (see Hubber et al. 2010). In the present context, it is thus necessary to find appropriate learning activities where students effectively undertake multi-representational reasoning about experiments, if conceptual learning and change from the latter is to occur. Note, that the aim here is specifically conceptual learning, and not laboratory work, problem solving, or any other of the possible educational benefits of MRs mentioned in above.

In the sequel, such type of learning activities will be presented, which is the study objective of this contribution.

One strategy to engage students to learn with MRs is the use of cognitively activating tasks. These kinds of tasks aim at implementing cognitively challenging learning strategies (Klauer and Leutner 2007) such as relating prior knowledge to new information, initiating cognitive conflicts, searching different ways to solve a problem, relating representations to others with equivalent or complementary meanings, as well as encouraging students to express their own thoughts, ideas, and concepts using various domain specific representations as cognitive tool (Stein and Lane 1996; Kunter and Baumert 2013).

10.1.3 Representational Activity Tasks (RATs)

In the present context, "cognitive activation" means that students think more often, more explicitly, and more deeply about experiment-related representations, express them, and draw conclusions from them as would be the case in a usual learning

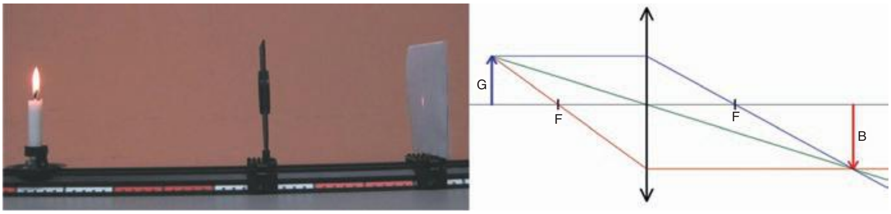


Fig. 10.2 Example of a RAT (TG) requiring mapping of two representations (showing two different imaging conditions) and a modification to achieve coherence between them (photograph as a realistic picture, ray diagram as a schematic representation) plus a short written explanation

setting, without adequate instructional means. The learning activities to achieve cognitive activation (in this sense) are a set of newly developed specific tasks, called "Representational Activity Tasks (RATs)", requiring learners to explicitly reason about and analyze various experiment related representations. Conventional tasks deal with the connections between representations most often implicitly, with a focus on content and a problem statement related to it (such as finding the optical image in a given lens arrangement), and based on the tacit assumption that the pertinent representational means to express this content and problem, and their connections (such as ray diagrams, and relating them to the experimental situation), will be used by the learner without explicitly asking for this. In contrast, RATs involve always two or more types of representations simultaneously, and explicitly ask students to elaborate on various connections between them, such as comparing, mapping, completing etc. MRs. An example of a RAT is given in Fig. 10.2, and details about the design principles will be given in 'Materials and Methods'.

Note that, while there are good reasons for potential benefits of MR based learning in the above sense, it creates also complex demands and increased cognitive load for learners (van Someren, ch. 12; see Ainsworth 2006, and literature cited therein). It is therefore a highly relevant question, whether an approach like RATs can indeed improve RCA and RCU/C in spite of these demands. On the basis of the above research background, the following general research questions are treated in the present contribution: What is the impact of RATs on (a) representational coherence (b) conceptual understanding when learning with experiments in ray optics?

Within the framework of a general overview and discussion of MRs in physics education in this volume, the focus of the present contribution is on results about these research questions and their interpretation, while detailed descriptions of the methodology of the pair study on RCA and RCC/U are given elsewhere.

10.2 Materials and Methods

10.2.1 Instructional Material and Intervention

In view of the background given above, the learning tasks aiming at representational coherence (RCA) and representation related conceptual understanding/change (RCU/C) require the following cognitive activities:

10.2.1.1 Representational Coherence Ability

Learners are required to carry out one of the following four different tasks formats requiring coherence between different representations ("coherence tasks"):

- compare and map representations
- complete/modify representations (in order to establish consistency between different RFs)
- find and correct errors in representations (based on information from different RFs)
- describe and explain their reasoning during the above activities.

Figure 10.2 shows an example of a RAT which involves mapping and modifying multiple representations. This RAT consists of two similar experimental settings containing a convergent lens, but with two different cases of image formation, viz. reduction (left) and magnification (right) of the object size (as determined by different relative values of object distance and focal length). These two settings are not expressed by the same type of representation, but by a photograph and a schematic drawing (ray diagram), and students are asked (i) to mark the differences between the arrangement of optical elements (ii) to adapt the schematic drawing, in order to establish coherence with the realistic representation, and (iii) to describe and justify their modification in a short written text. The task thus explicitly requires to link three different types of representations (realistic and schematic image, text). In contrast, the conventional task related to the same content asks to work with only one representational format, eg. to complete the image construction with principle rays (schematic image, see Fig. 10.3).

Note that in this and some other cases the CG tasks were just conventional applications of the ray model, and the requirements (as well as the written task formulation) were more difficult for the treatment group (TG) than for the CG. The comparison is not between tasks of equal difficulty, but between equal learning time, where a part of the conventional tasks has been replaced by the more demanding RATs.

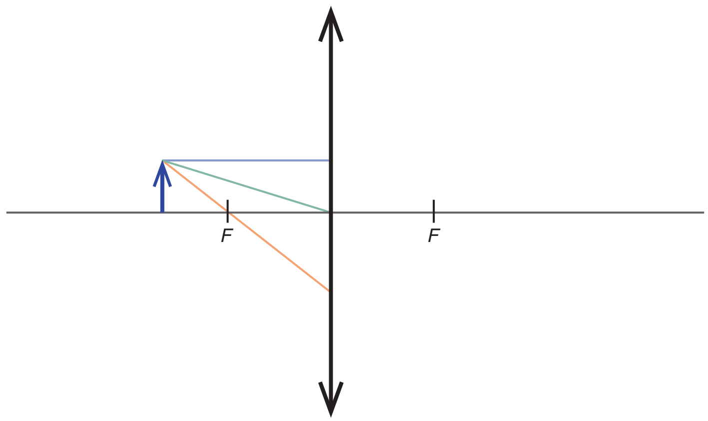


Fig. 10.3 Example of a traditional task (control group, CG) that focuses on only one type of representation, requiring to complete the image construction with principle rays (a typical type of task in the teaching of geometrical optics in the classroom setting of the target sample below)

Table 10.1 Conceptual difficulties treated in the RCC/U study (all taken from existing research, see text)

Relation between light propagation, scattering, and perception
Relation between light rays (model) and light beams (phenomenon)
Role of principal rays
Formation of real images (intersection of outgoing rays)
Formation of virtual images (intersection of prolonged outgoing rays)
Effect of covering parts of a lens
Aerial image

10.2.1.2 Representation Related Conceptual Understanding/Change

The learning tasks to foster this aspect of science learning required use of different representational formats for reasoning about common conceptual difficulties (see Table 10.1), all of which were taken from existing research in this domain (Goldberg and McDermott 1987; Wiesner 1986; Reiner et al. 2000). The TG students received specific MR based cognitive activation measures, mainly self-generation of MRs (in line with the findings of Waldrip et al. 2010), in some cases also completion of partially given MRs. An example is the visibility of the real image formed by a

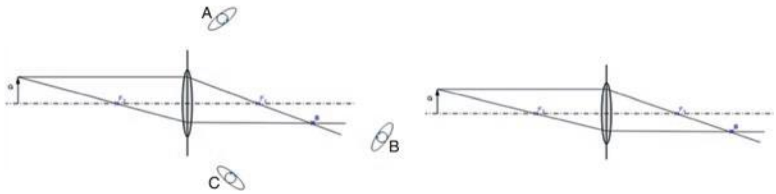


Fig. 10.4 Example of a RAT requiring analysis/reasoning concerning a conceptual difficulty related to the formation and visibility of real image by a converging lens. Learners are requested to reason on the basis of the ray diagram in order to explain which of the observers (*A*–*C*) could see the image with a transparent/opaque/no screen at point S

Table 10.2 Schedule of the unit on converging lenses and image formation (common for CG and TG)

Lesson	Content
1	Teacher experiment on converging lens: refraction, focus, principal rays, image construction
2	Students experiment about same content: variation of parameters, protocol, discussion
3, 4	Working sheets: image construction, different imaging cases
5, 6	Working sheets: lens formula, revision of unit

converging lens when a transparent/opaque/no screen is present (aerial image). A widespread conceptual difficulty is that the screen is necessary for (diffuse) reflection of the image, while it is not conceived that it would still be possible to see the image if the observer's eyes were located in the position of the screen (Goldberg and McDermott 1987). Figure 10.4 shows the related RAT (TG, left side), which asks to work with the ray diagram (schematic representation) in order to explain which of the observers (A – C) could see the image with a transparent/opaque/no screen at point S. The CG was merely asked to where the image would form, and from where it would be visible (not referring to the ray diagram). Hence, in the latter task the same conceptual difficulty was addressed, but it did not require to operate on the ray diagram.

The interventions for RCA and RCU/C were embedded in the regular curriculum and started when the topic of converging lenses and image formation had to be taught according to the official schedule. The teachers in all conditions implemented a detailed lesson plan, which was discussed and adapted according to their feedback before the intervention began. The lesson plan followed a well-established teaching sequence for the given subject matter.

The total length of the intervention was 6 lesson hours, see Table 10.2 for an overview (6 × 45 min, grouped in 3 double lessons of 90 min, a standard format for science teaching in Germany). The pretest for covariates and initial values of dependent variables and the post-test for the values of the latter after the intervention were administered in separate lesson before and after the learning unit. After having seen and interpreted a teacher experiment demonstrating the basic principles (1st lesson), students carried out and analyzed an experiment (2nd lesson) of their own, exploring further the basic content of the teacher experiment. They then worked on tasks about various aspects of the topic during a sequence of (4 × 45 min, 3th to 6th lesson). Student work was carried out in pairs.

While time-on-task and core learning content were identical in control and treatment groups (see Table 10.2), the learning tasks were differentiated according to the learning objectives of the two studies as explained above. For the RCA study, the TG1 instruction was enhanced by RATs focusing on representational coherence, i.e. with one of the four types of "coherence tasks" presented above; CG1 worked on additional conventional practice tasks instead. As an indication intervention strength, the number of representational formats N_{RF} necessary for a successful solution is 1½ times higher in the TG1 than in the CG1; the averages per item are 2.2 (≥2 per construction) and 1.5, respectively (the latter value is slightly higher than the average of 1.2/item obtained from an analysis of roughly 800 conventional textbook task, see Scheid 2013). For the RCU/C study, both groups followed also the content summarized in Table 10.2, TG2 using different representational formats for reasoning about common conceptual difficulties, also treated in the CG2 learning tasks, but without representational reasoning as cognitive activation measure. Note that CG2 is a control group only with respect to the use of RATs, but that a treatment takes place with respect to conceptual difficulties. As an indication intervention strength, the number of self-generated MRs related to conceptual difficulties/misconceptions is four times higher in the TG than in CG.

10.3 Design, Instruments and Analysis

A quasi-experimental pre-post design was used, for both the study on RCA and on RCU/C. Together, there were four groups in the two partial studies, see Table 10.3 (all based on the standard lesson plan for geometrical optics, see above). There were two types of treatment groups with an instruction enhanced by RATs (as explained in the preceding section) focusing on representational coherence (TG1), and on conceptual difficulties and conceptual change (TG2). The control groups (CGs) did not learn with RATs, the first with conventional learning tasks instead (CG1), the second with learning tasks dealing with the same set of conceptual difficulties, but not requiring explicitly to operate on a given representation, e.g. a ray diagram (CG2). This design allows for the following comparisons: TG1 and CG1 will be compared in order to know whether RCA can be fostered by the RAT approach;

Table 10.3 Design table of the two interventions: Without/with RAT intervention × without/with conceptual change (CC) intervention (no/yes)

		RAT	
		n	y
CC	n	CG1	TG1
	y	CG2	TG2

TG2 will be compared to CG2 and CG1 in order to know, whether RCU/C can be fostered by RATs as well as by learning tasks targeted at the same conceptual difficulties without a representational focus (comparison with CG2), and whether there is any appreciable advantage at all compared to learning without addressing difficulties (comparison with CG1). Up to the intervention, TGs and CGs were identical in their content, lesson plans, number of learning tasks, and duration of the learning sequence (6 weeks); moreover, corresponding TG and CG classes at the same school were taught by the same teacher.

The investigation took place within regular secondary level I physics classrooms in the German state "Rheinland-Pfalz" (N(RCA) = 167 (CG), 175 (TG) at six different schools; N(RCC) = 250 (CG), 275 (TG) at ten different schools; age group 13–15 years, average 13.5 years, 7th and 8th grades of German school system, mostly from academic track schools ("Gymnasium[3]"; Scheid 2013; Hettmannsperger 2015). Subject matter was geometrical optics (light sources, light propagation and rays, shadows, lenses, image formation), a standard topic according to the teaching program of this age group. The length of the interventions was about six lessons ($6 \times 45' = 4.5$ h in total). We now turn to a description of covariates and instruments used.

In order to control for possibly different factors in CG and TG, in the RCC study pre-test values, relevant school grades (mathematics, physics, and German language), gender and class-size were taken into account as covariates. Moreover, three subscales of cognitive ability related to different representational formats (word associations, numbers, and visual/spatial imagination) were considered (Liepmann et al. 2007). For the RCA study the same covariate set was considered (except class size, as classes were not distinguished in the 2-level model considered, see below). Moreover, in order to look for potential effects of the interventions on motivation, a test based on well-validated instruments taken from the literature was used (Hoffmann et al. 1997; Rheinberg and Wendland 2003; Kuhn 2010); reliability was satisfactory across all intervention groups ($\alpha_C > 0.9$).

Instrument for RCA In order to assess their representational coherence ability of learners, test items required to relate real phenomena und experiments to various types of representations and multiple representational formats to each other. Types of coherence relationships to establish were comparing and mapping MRs, as well completing and correcting given incoherent MRs; additionally, participants had to describe and explain their reasoning while resolving these questions. Thus, the test contained the same cognitive processes as the RAT intervention, but of course different tasks. Moreover, in half of the items reasoning about multiple representations was not explicitly asked for, but implicitly necessary for solving the question; this is an essential and widespread role of MRs in scientific work and thus has a high curricular validity (see Fig. 10.5 for an example of a physics "word problem" of this kind).

A pilot study was carried out in the same age group and classroom setting as the main study, improving item formulations and detecting items which did not work properly according to the desirable ranges (Ding and Beichner 2009). Moreover, an

Ines would like to draw an enlarged image (20 mm) of a lady bug that originally has a size of 5 mm. To facilitate drawing, she wants to project an image of the bug onto a screen. The lady bug is located 10 mm in front of an appropriate lens.

At what distance should the screen be positioned?

Solve the task with a calculation.

Fig. 10.5 Example of an item assessing RCA indirectly (calculation with data contained in textual form)

expert rating with 11 experienced teachers (on average 15 years of teaching experience) yielded satisfactory curricular validity for the remaining items (intra-class correlation 0.5 < ICC < 0.7). There were 15 items retained for the main study, for which we obtained the following instrument characteristics for the post-test (pre-test values cannot be expected to be in the desired ranges, as there is no consistent knowledge yet). Overall internal consistency was $\alpha_C = 0.79$ (across different validation samples), testing for exclusion of the individual items did not lead to an increase. Item difficulties were between $.2 < p < .8$, item-test correlation were $r_{it} > .3$ (up to slight deviations for a few exceptions). Thus, the test characteristics are in the desired value ranges according to the literature (Ding and Beichner 2009). A detailed report on the RCA test is available in Scheid (2013).

Instrument for RCU A concept test for geometrical optics (with focus on image formation by lenses) was developed and validated in the same way as for the RCA test, dealing with the core concepts of light propagation, scattering, formation of real and virtual images, and visual perception of optical images. In a pilot study in the same age group and classroom setting as the main study, items were tested for necessary improvements of their formulations and for item characteristics in the desirable ranges (Ding and Beichner 2009). The test was designed as multiple-choice-test with remaining 11 items (test duration 15 min), each of which had the scientifically correct answer and three distractors as answer options (see Table 10.4 for example items; Hettmannsperger 2015). Distractors were based on widespread intuitive students' concepts reported in literature (Goldberg and McDermott 1987; Wiesner 1986; Reiner et al. 2000). Instrument characteristics for the post-test (as in in the RCA study, see above) using the whole sample of both the RCA and RCC study are as follows: Item difficulties ranged between $.2 \leq P_i \leq .8$ and item discrimination indices between $.25 \leq r_{it} \leq .45$. Internal consistency attained a satisfactory level ($\alpha_C = .75$). A detailed description and analysis of the concept test is available in Hettmannsperger (2015).

In the RCA study a two-level model specifically adapted for the measurement of change (Heck et al. 2014; Göllner et al. 2010) was used (level 1: measurement times, level 2: intervention groups). It allows to analyze students' learning progress over time in a way which has several advantages when compared to repeated measurements analysis of variance (treatment of missings; less strict applicability requirements; more flexibility in the form of the temporal development; Göllner et al. 2010). In the RCU/C study with higher number of classes/schools, a three-level model was implemented (level 1: measurements times; level 2: learners;

Table 10.4 Sample items of the concept test

Scientific concept	Sample item
Ray model	Which statement is correct?
	Light rays are something real, like thin water jets from a spray gun
	Light rays exist only in peoples' minds, e.g. like constructions in geometry
	Light rays are exactly the same as light beams
	Light beams are mental objects, for example they are used to determine the image size
Scattering and visibility	Which of the following objects/creatures can be seen in a completely dark room?
	A glowing firefly
	A white sheet of paper
	A bicycle reflector
	The eyes of a cat
Image formation	In an experimental assembly a light bulb, a converging lens and a screen are set up so that an enlarged, inverted and sharp image of the filament is formed. What will happen if the bottom half of the lens is covered?
	The upper half of the image will be cut off
	The bottom half of the image will be cut off
	The image will become darker
	The image will become brighter

level 3: classes) (Fahrmeir et al. 2009). In both studies, proper treatment of variances (eg. entering the calculation of effect sizes) for the nested structure of the samples is of course a main advantage of multilevel analysis. Due to the focus of the present study, which is a discussion synthesizing the main effects of the two related interventions and to lack of space, details about the multilevel analyses are given elsewhere (Scheid 2013; Hettmannsperger 2015).

Finally, effect sizes between CGs and TGs were computed as Cohen d (using pooled variance) according to standard procedures (Cohen 1988; Tymms 2004). Additionally, the Hake index (Hake 1998) as a measure of the learning gain was computed.

10.4 Results

The data revealed several main statements about representational coherence and conceptual understanding, best discussed on the basis of Fig. 10.6 (see Table 10.5 for numerical values):

Initial Situation (Pretest Values) Control and treatment groups started approximately at the same level for both RCA and RCU/C; there was in fact a slight but statistically not significant advantage in favor of the CG in both cases (beyond

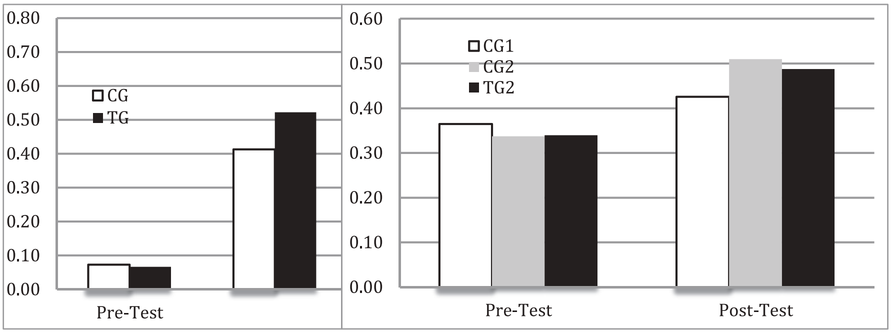


Fig. 10.6 Descriptive values of RCA (*left*) and RCU/C (*right*) in the pre- and post-test (normalized to the maximal value of the relevant test in each case; for standard deviations, see Table 10.5)

Table 10.5 Descriptive values of RCA and RCU in the pre- and post-test (normalized to the maximal value of the relevant test in each case)

		CG1	TG1	CG2	TG2
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Pre	RCA	0.07 (0.19)	0.07 (0.07)	n.t.	n.t.
	RCU	0.36 (0.14)	0.37 (0.14)	0.34 (0.15)	0.34 (0.15)
Post	RCA	0.41 (0.13)	0.52 (0.13)	n.t.	n.t.
	RCU	0.43 (0.17)	0.43 (0.17)	0.51 (0.24)	0.49 (0.21)

Notes: Significance level of all pre-post changes: $p < 0.001$
Significance level of group comparisons: TG1 vs. GC1 and TG2 vs. CG1 $p < 0.001$, TG2 vs. CG2: n.s. (see text for discussion)
n.t. (not tested): RCA was not investigated in study 2

visual inspection, these differences were taken account of in a more formal manner as covariates, see sec. "Design…" above).

Intervention Effects (Pre/Post and CG/TG Comparisons) After the intervention, both control and treatment improved for both variables in question. For RCA (TG1 vs. GC1), the RAT treatment led to a sizeable advantage compared to the control group ($p < 0.001$, $d = 0.6$[4]). For RCU/C, there is no significant difference between learning tasks addressing common conceptual difficulties with and without a representational focus (TG2 vs. CG2), but such a difference occurs when comparing to learning without addressing these difficulties at all (TG2 vs. CG1; $p < 0.001$, $d = 0.4$). In terms of the Hake gain index $g = (R_f - R_i)/(1-R_i)$, where $R_{i/f}$ are the initial and final score, respectively, relative to the maximal possible gain (Hake 1998), one has the following results: the RCA control and treatment group achieve a $g_{CG}(RCA) = 0.4$ and $g_{TG}(RCA) = 0.5$, respectively; for RCC the values are $g_{CG}(RCC) = 0.1$ and $g_{TG}(RCC) = 0.2$.

With regard to covariate influences, grades in mathematics (medium effect size) and physics (small effect size), as well as visual/spatial imagination abilities (small effect size) were found to have significant effects on the learning gain, but without a difference between the CG and the TG groups. For other subscales of cognitive ability, German language grades and gender (as well as class size for the RCC study) (in the RCC study, additionally class size) we did not find any significant influences. Moreover, there were no significant motivation differences between TG and CG neither in the pre- nor in the post test (see Hettmannsperger 2015; Scheid 2013).

Intervention Comparison Even though on a formally identically scale (from 0 to 1, by normalization to maximal test value), the absolute results for RCA and RCU/C cannot be directly compared. There are however two features which deserve attention: First, the pre-test values of RCA relative to the maximal score are very low (the test is related to specific physics content which had not been treated before according to the teaching program), pre-test values of RCU/C, again as compared to maximal score, are noticeably higher (it is the very idea of concept tests that its items can be understood even before formal teaching on the given subject it, in order to diagnose conceptual difficulties (and their possible change); see eg. Engelhardt (2009) for a methodological paper, and many applications of the FCI, see Coletta et al. (2007) and references therein). Second, there is a large difference in relative increase, RCA improves much more than RCU/C. In terms of the Hake gain index values just given, there is a factor of almost 4 (CG) and more than 2 (TG) for the difference in relative increase of RCA and RCU/C, a point to be discussed below.

10.5 Discussion

When comparing the two multiple representation based treatments aiming at either improvement of coherence (RCA) or at conceptual understanding/change to the control groups learning without such a representational focus (but otherwise comparable), we obtained the following results about possible influences of covariates and about the main effects of the intervention. On the lowest level of the multilevel analysis (measurement times/individuals), no influences of cognitive abilities related to two RFs (words, numbers), nor of German language grades and gender were found. Grades in mathematics and physics had a significant influence on learning gain (medium and small effect size, respectively), consistent with the famous statement by Ausubel (1978) about previous knowledge as essential predictor of learning. As geometrical optics is by definition related to geometry, and as a lot of mathematics teaching is about geometry in the age group of our sample, the somehow stronger influence of mathematics compared to physics is not completely implausible. Moreover, visual/spatial imagination abilities also had a significant effect on learning gains (small effect size). Again, it is not implausible that this component of cognitive abilities influences learning in an area which has a lot to do with geometric properties and constructions, while the abilities related to words and numbers have not. The two preceding covariate influences (math grades, visual/spatial abilities) are interesting points to be considered more in detail in the future, both for a better scientific understanding of MRs, and for classroom practice.

On the higher levels (groups), statistically very highly significant advantages with noticeable effect sizes concerning the interventions (TG versus CG) were found for both RCA and RCU/C ($d = 0.6$ and $d = 0.4$, respectively; $p < 0.001$ in both cases). Note, that these results were obtained with a series of control measures to ensure comparability (in particular same teacher, comparable initial situation, control for remaining differences by taking account of several covariates; see above). Moreover, on the level of classes in the RCU/C study, class size did not have an influence on the outcomes. Finally, none of the covariates discussed above showed a difference between the CG and the TG groups.

Thus, the beneficial effects of RATs found both for representational coherence and for conceptual understanding show a certain stability with regard to possible individual and classroom influence factors; see however, an important caveat discussed at the end of this section.

For RCA, there are at this time only few classroom interventions specifically targeted at improvement of coherence of multiple representations, and a medium effect on group level size in this state of research can be considered as satisfactory. The study provided also insight for further improvement of the approach and its analysis. First, a set of RATs dealt with the derivation of the magnification equation and turned to be slightly too difficult in its present form. Appropriate scaffolding (hints, intermediate steps) could lead to further improvement. Second, the intervention covered tasks referring to two different experiments (propagation of parallel light beams through a converging lens and image formation with a converging lens). With a longer intervention, additional experiments could be included within ray optics.

The analysis in this contribution is also restricted in the sense that the effects presented are based on the whole RCA instrument. Further analysis can focus on inter–item-differences to identify specific areas with conspicuously small learning gains, indicating potential learning obstacles, and the necessity of a more effective learning support (either by RATs or another approach), or on the contrary with high learning gains, potentially improving the understanding of the instructional features which make a RAT effective (the same holds in a similar way for the RCC study).

For RCC, the effect size is still acceptable, as the "persistence" of conceptual difficulties is well known: conceptual change is notoriously hard to achieve (see Schnotz 2006; Galili and Hazan 2000, for the subject matter of ray optics in particular), and classical strategies like inducing cognitive conflict by demonstration experiments do not automatically lead to success (Limòn 2001; Vosniadou 2013). The multiple representation based learning tasks turn out to be as effective as learning tasks addressing the same conceptual difficulties without a representational focus, and the effect size values come out at least at the threshold ($d = 0.4$) of noticeable real-world differences known from meta-analysis ("hinge point", Hattie 2009). Note, that this is a result on the general level of the RCU instrument used, and we do not address conceptual change for specific conceptual difficulties here (this would require a discussion on the individual item level, which we do not present in this contribution).

On the one hand, the positive effects found are good news, as (multi-)representational reasoning requires an additional cognitive activity and thus creates additional cognitive load potentially harmful for learning. But as the results show, this is not the case for RATs, and as MR based reasoning is known to be essential also for other important objectives of science education, it is a promising state of affairs that appreciable positive effects on conceptual understanding are as well among the benefits of this instructional approach and can possibly be combined with these other objectives. On the other hand, in view of this very potential of representational reasoning for science learning in general one could have expected that it should be a more effective conceptual change strategy than addressing the same conceptual difficulties without a representational focus. This then leads to limitations and open questions of the present work, which will be addressed below.

Under another perspective, the Hake gain index complements these results of an overall learning effectiveness of the two representational learning approaches. For RCA, the TG value g = 0.5 obtained is comparable to those of the treatment groups provided by other methods of cognitive activation ("interactive engagement") in the large comparison study of Hake (1998). For RCC, however, the TG value of g = 0.2 is the one of the traditional groups studies by Hake (1998). In terms of learning gain, the RCC effects do not seem satisfactory, and this leads again to the discussion of limitations and open questions, addressed in the following section.

With respect to above results, in particular the effect sizes found, we would like to point to a limitation of the present work. The investigated samples (342 students and 12 classes at 6 schools for RCA, and 525 students and 21 classes at 10 schools for RCC, respectively) are large enough to cover a considerable range of individual, class and school conditions, and thus to justify a degree of representativeness for the given classroom setting comparable to other studies in physics education. However, this setting is largely that of the German academic track schools (see), which entails the following possible consequences: First, as existing research points to an appreciable association of academic success and working memory (Gathercole et al. 2004), and as cognitive load is one of the main problems with MRs (see Sect. 10.1.3), our finding that cognitive load does not impair the positive effects of RATs has to be checked for learner groups with lower cognitive abilities. Second, in a sample including learner groups of this kind, the variance in outcomes might be larger, while the difference of averages of CG and TG might be smaller (according to the preceding argument) than in the sample analyzed here, both leading to smaller effect sizes; in this sense, effect sizes reported here belong a priori to academic track students, and generalization to other students has do be done with a caveat, or on the basis of new data.

10.6 Conclusions and Outlook

We may conclude that representational activity tasks (RATs) discussed in this contribution can foster two kinds of educational objectives related to physics experiments:

First, representational coherence ability (RCA) which deals with correctly and fluently combining, mapping and correcting multiple representational formats essential for proper understanding of and learning from experiments (or observations), from the level of "operational" or "enactive" manipulation of the experimental devices and materials to the most abstract level of the mathematical formulation of the law of nature underlying (or investigated) in a given experiment.

Second, representation related conceptual understanding and change (RCU/C^2) which deals with a link between scientific experiments and their conceptual basis and significance, with a special focus on conceptual difficulties, and requires the learner again to reason with multiple representations at different levels of abstraction as just mentioned, such as describing observed phenomena by oral or written language in terms of appropriate concepts, or expressing experimental results by schematic diagrams or mathematical relations containing formal representations of these concepts.

The focus in the case of RCA is coherence of multiple representations, in the case of RCU/C their role for conceptual understanding. Effect sizes are of medium size for the former ($d = 0.6$), and between small to medium size for the latter ($d = 0.4$). This holds for realistic teaching conditions in regular classrooms.

With regard to classroom practice, RATs thus appear as a useful element of the physics teacher's toolkit of reasonable practical relevance. The effects for RCA are stronger than those for RCC, but we found that at least (i) there was no harmful cognitive load created by the extra requirement of the MR reasoning activities, and (ii) that even for RCC the effects are as large as for learning tasks with the same conceptual obstacles, but without MRs. This then, leads to several perspectives for future research.

Subsequent investigations could look at a combined approach, which in the same time aims at conceptual learning and other objectives of (multiple) representations for the learning of science, in particular representational coherence. Is it possible to adapt the RAT instructional design in a way, where the presence of positive learning effects and the absence of harmful cognitive load, found in isolation for RCA and RCC in the present study, will be maintained in the combined approach? Another highly relevant question is whether it is possible to improve the effects of RATs on conceptual learning, found to be smaller than desirable. In view of the persistence of conceptual obstacles/misconceptions it seems reasonable to combine RATs with other forms of cognitive activation, eg. through forms of peer/group debate (confrontation) of these obstacles (see e.g. Thorley and Treagust 1987; Zimrot and Ashkenazi 2007). Finally, a more general objective is of course to investigate RATs in other domains of physics (science) rich in MRs, such as mechanics.

We hope that the two related studies presented here, with their focus on experiments on the one hand, and coherence and conceptual significance of MRs on the other, can serve as a useful and interesting contribution for the state of the discussion as presented in this volume.

10.7 Notes

1. Many statements of this contribution are formulated with respect to physics education, but could be generalized to science education; this should be kept in mind, even when it is not explicitly stated everywhere.
2. As we have to distinguish conceptual understanding (at a given stage or time) and change (between two stages or times), we use RCU and RCC, respectively, in order to distinguish the two.
3. See the "TIMSS Encyclopedia" (Mullis et al. 2008) for background about the German school system.
4. We follow the usual convention of effect size levels as small, medium and large with $0.2 < d < 0.5$, $0.5 \leq d < 0.8$ and $0.8 \leq d$, respectively (Cohen 1988).

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Chapter 11
Understanding and Promoting Effective Use of Representations in Physics Learning

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11.1 Introduction

Selecting, coordinating, and moving among representations are essential skills of practicing physicists. While the physics education community has made great strides to broaden the goals and methods of instruction at the introductory college level (Docktor and Mestre 2014; Redish 2014), explicit attention to student use of representation has been less prevalent. This chapter addresses empirical studies of student use of representation and examines approaches that promote their effective use in physics learning.

As we seek to unpack the roles of representation in physics learning, it is useful to consider a specific example – take the ubiquitous "Bohr model" of the atom. This model, while incomplete and flawed, is highly productive and often used as a tool in the education of students. McKagan et al. (2008) argue that the atomic Bohr model can be a helpful stepping-stone to bridge between classical and quantum perspectives. Furthermore, it provides a useful example of how representations and physical concepts are intertwined. The Bohr model of the atom depicts the atom with a core nucleus and surrounding electrons in fixed orbits, drawing an analogy to the orbits of planets around the sun (Fig. 11.1a). This model accurately predicts energy levels of the electrons and emission spectra (Rydberg spectrum) for hydrogen and hydrogen-like atoms. When it comes time for students to learn about these energy levels, it is often sufficient for students to manipulate the relevant mathematical representations such as the Rydberg formula. But does understanding lie simply in

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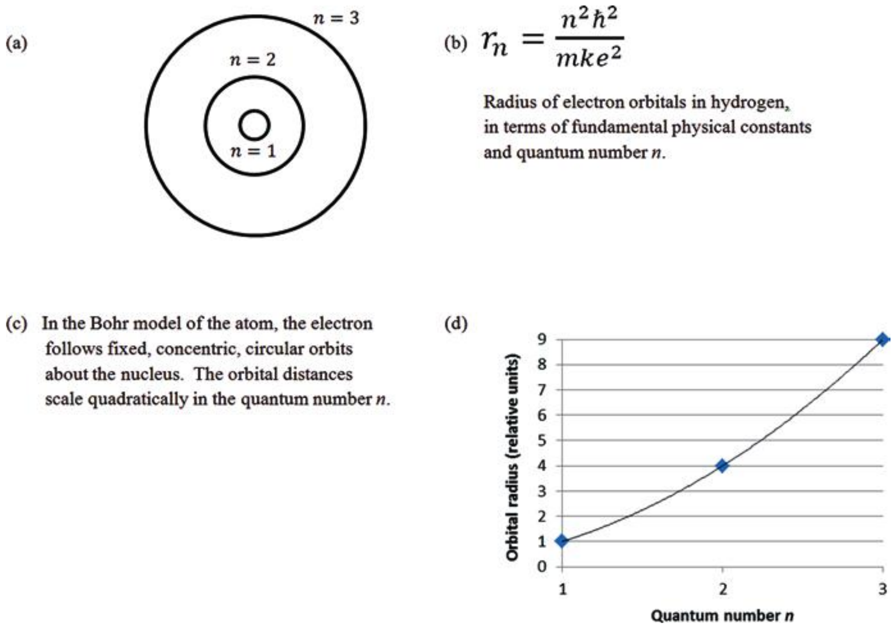


Fig. 11.1 Representations of the Bohr model of the atom (**a**) pictorial, (**b**) mathematical, (**c**) verbal, (**d**) graphical

those manipulations, or does it include the ability to construct, interpret, and move between additional categories of representation like diagrams and graphs?

While the effective use of representations is an essential component of introductory physics, it remains largely an implicit focus of attention. There is no content that appears absent of representational framing; however, the content is largely presented (and often perceived) as independent of whatever particular representation is being used. A common but unstated assumption is that if students answer a question (e.g., about energy levels of the hydrogen atom) in one format (e.g., mathematical representation) they will be able to answer questions in other forms (e.g., graphical formats). We challenge this assumption, and the associated belief that mastery of content can exist independent of representation.

We synthesize several of our prior studies (Kohl and Finkelstein 2005, 2006a, b, 2008; Kohl et al. 2007) to present a series of empirical studies on undergraduate students' use of representation in introductory physics in order to describe when and how students use representations, and to understand the impacts of varied instructional strategies on student performance with representations. Explicitly, our research questions are:

I. Can the manner in which an introductory physics problem is represented significantly impact student performance?

II. To what extent do students in our introductory college courses possess the ability to assess their own competence with representations? Can they productively choose between them when solving problems?
III. Do instructional environments with significantly different representational content (i.e. more representations used in the presentation of a particular topic) lead to more and/or different student skills with representations?

11.2 Theoretical Backdrop

We draw from socio-cultural perspectives on defining representations and their use (Cole 1996; Engestrom 2005; Vygotsky 1978). From such perspectives, humans' higher order cognitive processes are mediated by culturally bound artifacts or tools (Cole 1996; Vygotsky 1978). That is, students use language and other human-constructed artifacts (math, lasers, measurement systems, etc.) as they learn about given concepts (electromagnetic radiation, gravity, etc.). In our case, we consider representations as these key tools and as artifacts that mediate students' cognitive processes in solving physics problems. In the present case studies, we focus on four representational formats that mediate students' understanding of physical systems: (See Fig. 11.1 for examples.)

– Verbal: Written sentences expressing an idea or concept.
– Mathematical: Equations and associated symbols.
– Graphical: Graphs of mathematical functions or of the relationships between the different quantities used to describe a physical system
– Pictorial: Images or schematics of a physical system or a situation strongly associated with that system.

DiSessa (2000) provides an excellent example for considering how representation mediates cognitive processes. Galileo, a genius, spends two pages proving that two objects traversing at the same constant rate will travel relative distances that are proportional to the amount of time they spent traveling. That is, given

$$distance = rate \times time$$

and a fixed rate, then we have the ratio

$$\frac{distance_{object\,1}}{distance_{object\,2}} = \frac{time_{object\,1}}{time_{object\,2}}.$$

Remarkably, Galileo proves this using geometry, because algebra (a representational system) had not been codified yet. Now that algebra exists, such explorations are routine in K-12 education. A new tool (in this case, a new representational format) allows for new understanding.

While representations are the primary artifacts we focus on, we also attend to the social construction of the classroom environments also mediating cognitive processes. Activity Theory, like other socio-cultural theories derives from the work of Vygotsky (1978) and others (Davydov and Radzikhovskii 1999, Leontiev 1978), provides a productive lens from which we might characterize the outcomes from the complex interactions among the students, representations used, and environments in which students are learning (Cole 1996). Activity Theory advances this earlier socio-cultural historical work by noting that these representational artifacts are bound in social systems – it takes a holistic approach, expanding the basic unit of analysis from an individual in mediated action to include the broader interplay of the individual with the situated contexts (Kaptelinin and Nardi 2006) – in our case to learning environments. While Activity Theory identifies essential defining elements of such learning environments (rules, community, and division of labor), we will focus on the norms of how representations are used in differing instructional environments. Thus, we collapse the situational characteristics into a single form of mediation and focus on two key elements of students' cognitive processes (and performance) – the representations used and the normative expectations of their instructional environments. For a more detailed review of activity theory and the broader suite of socio-cultural historical activity theories, Cole (1996) and Daniels (2009) are good sources.

Building on this activity-theoretic perspective, we note that these representations are socially/situationally bound in several senses. Different cultural systems allow for different tool sets and for their uses in different ways. For example, mathematicians and physicists use the same symbols and formalisms (rules about symbol use) rather differently (Redish 2006). A common example that readers may note is the conventional labeling scheme for a spherical coordinate system – mathematicians and physicists commonly reverse the role of θ and ϕ. Furthermore, the object of focus can shape the meaning of the representation itself. Just as the object of focus is bound by representation, so too can the representation take on meaning based on the object of focus – a graph of a sine wave in the context of mechanical waves will be taken to represent particle displacements by default, whereas in the context of electromagnetism, it may be taken to represent field amplitudes or, as often is the case, misunderstood as the path that light travels (PhET 2015). As such, we find that the content of physics, the representations used, and the environments in which they are used cannot be uniquely separated.

This perspective brings a variety of implications. First, understanding of a concept takes on a broader definition – knowing and applying concepts requires the ability to apply these ideas across a variety of representational formats. We posit that any *application* of physics content (e.g., solving a physics problem) will be bound by representational format. Additionally, because content and representation are bound by the cultural systems in which they are used, we can create various norms (within the situational contexts of our classrooms) that lead to different forms of expertise. Put simply, we expect that thoughtful construction of our educational environments can lead our students to perform differently, developing enhanced capacity to use (and perhaps understand) representational formats effectively.

In the following studies, we use this activity theoretic perspective to examine situational aspects of individuals' responses to prompted questions in class and on homework. We note that these students will be arriving from differing situational environments and anticipate both the representational format and the environments in which students are engaging with in these exercises to play key roles. As such, we hypothesize that: (i) representations will play a crucial role in students performance and hence different representational formats will impact student performance, (ii) given that meta-representational competence can mediate student performance (diSessa 2004), students' abilities to assess their own representational competencies will impact performance, and (iii) environments rich in representation use established norms and expectations that improve student performance across representational formats.

To address the research questions and associated hypotheses introduced above, we conducted two sets of studies. The first set examined the first two research questions by assessing student performance on isomorphic questions presented in various representational formats. While we acknowledge that the representations used in physics problems can be categorized in different ways, we choose to identify problems as described above: verbal (primarily involving written language), mathematical (primarily involving direct calculation), graphical (primarily involving explicit graphs of one quantity versus another), or pictorial (primarily involving diagrams or schematics representing the physical situation at hand). We also note that these representational formats span the bulk of representations used in traditional physics textbooks and problems presented to students in an introductory physics course. In these studies, we also begin investigating student meta-representational competence, which we define broadly as knowledge about the affordances and constraints offered by various representational formats, and an understanding of one's own competence in using different representations. To this end, we allow some students to choose the format in which their tasks will be presented and document variation in performance based on whether students work in preferred representational format.

Our second set of studies examines the impact of the instructional environment more directly by explicitly quantifying the representational content of the lectures and examinations in different courses. We then check whether differences in lecture/examination content lead to different student performances (for example, less sensitivity to representational format). The specific methods are discussed in more detail in the appropriate sections.

11.3 First Study Set: Student Performance Across Representational Formats and Impacts of Student Choice

An early goal of our work was simply to establish whether or not representation mattered. That is, we wished to determine whether presenting problems in different representations, even if those problems were isomorphic from the point of view of a physicist, would provoke substantially different performances from students. This initial study also began to investigate meta-representational skills by giving students a choice between different representational formats: Does allowing students to work in preferred representational formats have a measurable impact on performance?

11.3.1 Setting, Students, and Methods

Our studies focused on traditional (approx. 18–21 year old) undergraduate students in introductory large-enrollment (N = 300 to 600 students) algebra-based college physics courses at the University of Colorado – Boulder. The course sequence serves as a core requirement for the life-sciences, but not other sciences or engineering that require a calculus-based sequence. The two-term sequence includes both a lecture/theory based section (35-min meetings per week of about 300 students led by a single faculty instructor) and a combined laboratory & recitation section (a single two-hour meeting per week of about 30 students led by a single graduate teaching assistant, where students either work through simple experiments (laboratory) or do small group work centered around conceptual and mathematical problems (recitation) to complement the theoretical work presented in lecture. The first semester course (Physics 101) covered traditional Newtonian mechanics, energy, and an introduction to waves. The second semester course (Physics 102) covered electricity and magnetism and modern physics. These studies included both classroom- and homework-based studies and interventions (N about 300). All students in these courses participated in described activities, though presented data generally only involves those students that completed all assigned tasks.

The first course in this study set was the second-semester class, Physics 102. The format of the course was mostly traditional lecture (presentation of information via chalk-board), albeit with occasional in-lecture qualitative and quantitative concept tests using a personal response system (iClicker 2015). The second course studied was the first semester class (Physics 101). This course precedes 102 in the standard sequence, but this particular 101 section took place the semester following the 102 class mentioned above, and so each group was being exposed to the study for the first time. The two courses were taught by different professors, with different pedagogical approaches (described in later sections). The 101 class was largely transformed, with heavy use of interactive concept tests (Mazur 1996) and an emphasis on tightly integrated lecture demonstrations (Sokoloff and Thornton

Table 11.1 Summary of overall study structure, including course studied, semester (chronological), research questions addressed in each, instructor of each course, and our assessment of the style of the course (traditional lecture vs. PER-based reforms)

Semester of study	Course studied	Research questions	Instructor	Course style
First	Phys 102	I, II, III	A	Traditional
Second	Phys 101	I, II	B	Reform
Third	Phys 102	I, II, III	B	Reform

2004). In a follow-on study in this first set of studies, we review performances the students enrolled in the Physics 102 course that was taught by the same professor as reported in the Physics 101 study. This follow-on study allowed us to control for instructor and pedagogical effects that will be discussed in later sections. In Table 11.1, we summarize the overall structure of the sequence of courses in which we collected data for the studies featured in this chapter.

The students in each of the courses participated in the same number of lectures, tutorials, and laboratory sessions (about 45 lectures and 15 laboratories/recitations). The recitations focused on working through problems rich in context in small groups, with some demonstrations and some time reserved for homework and exam questions. The laboratories, alternating with the recitations on a weekly basis, were a mixture of directed work, open-ended questions, and testing predictions.

These studies featured a variety of instruments, including but not limited to analyses of standard exam and homework questions, use of study-specific questionnaires and homework, and observations of class time. These instruments and data-sets will be discussed in more detail (as appropriate) below, and are available in their entirety in Kohl and Finkelstein (2005, 2006a, b).

The first part of our first set of studies was to ascertain the impact of representational format on student performance, focusing on research question I. For two subsequent terms (first Physics 102 and then Physics 101 courses, respectively), we administered several questionnaire and homework problems written specifically for this study that held the “content” fixed and varied the representational format. The second part of this initial set of studies examined the performance impact of letting students choose among representational formats. In this part of the study, a treatment group (described below) was allowed to choose the representational format they preferred for an in-class questionnaire, while a control group was assigned a questionnaire in a random format.

For the Physics 102 class, we performed trials in two different content areas during two different weeks: wave optics and atomic physics. All students were assigned the same four multiple-choice homework questions that covered the same concept in four different representational formats, as well as a one-question multiple-choice questionnaire (in one of four representational formats) given in recitation. These homework problems were assigned online as pre-recitation questions and were turned in at the start of the recitation section. Students were expected to turn in pre-recitation homework each week and were prepared for the possibility of quizzes and questionnaires, and so these study materials did not represent a major departure

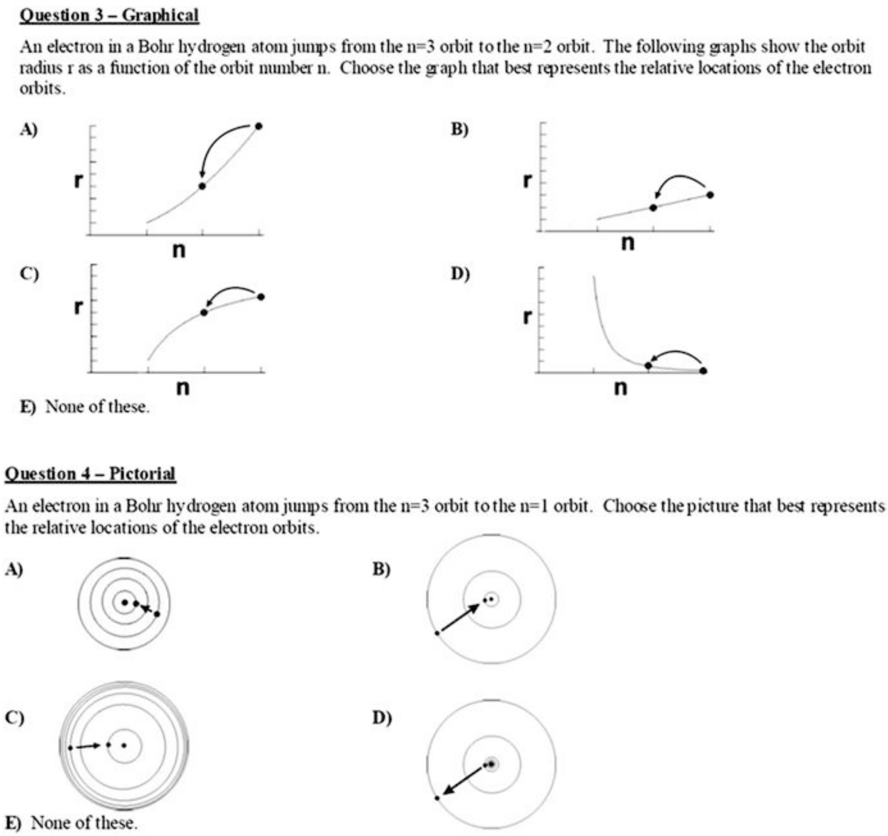


Fig. 11.2 Isomorphic homework problems (in graphical and pictorial/diagrammatic formats) regarding Bohr-model electron orbit radii

from the norm – as part of this class, students routinely saw such tasks regardless of whether they pertained to the studies described. The study questionnaires were administered by their section instructors (graduate teaching assistants) who were told to collect the data but were not informed of the nature of the study.

An example of two of the four homework problems (graphical and pictorial formats) from one of the two Physics 102 assignments is shown in Fig. 11.2. Each student completed all four homework problems prior to arriving to class. After turning in the homework, the students were given a one-question questionnaire in one of four representational formats. These questionnaire problems were isomorphic from format to format, with the answers and distractors mapping from one format to the next. It is worth noting that we use the word 'isomorphic' to mean isomorphic from the point of view of a physicist. A student may have a different view of the similarity (or lack thereof) between these problems (Chi et al. 1980).

Table 11.2 Summary of interventions for first Physics 102 trial

	Homework	Recitation questionnaires	Topics
Control	Four problems per topic	One per topic, format randomly assigned	Wave optics, atomic physics
Treatment	Same as control	One per topic, choice of format	Same as control (wave optics, atomic physics)

Note: All students received four homework problems in four different representations for each of two topics. All students received a one-question questionnaire for each topic. The treatment group was allowed to choose the representational format of the questionnaire; the control group had one assigned at random. Following trials used similar structure

Nine of the thirteen 102 recitation sections (N = 160 out of a total of 230 students) were allowed to choose from among the four representational formats on the questionnaire without getting to see the problems before making their selection. Note that we intentionally assigned more sections to the treatment group (choosing which format) to increase the chances of there being useful numbers of students selecting each available representation. Our intent was for the students in this treatment group to make their choices based on their previous experiences with representations in classes and on the homework assignment; notably, students did not receive feedback on the homework prior to choosing a questionnaire format. In the other four sections, we distributed questionnaire formats to the students randomly; these students served as a control group for our examination of the impact of representational choice on student performance. The treatment and control sections did not change from one topic area to the next, and the students in the two groups performed similarly on the study homework, the course exams, and in the course overall. Both the questionnaires and the homework counted towards the students' recitation scores for participation but were not otherwise included in student grades (e.g. for performance). The structure of this first trial is summarized in Table 11.2.

Similarly, in the second part of the first set of studies, in the subsequent semester, the homework and questionnaires in Physics 101 covered two subject areas: energy (in particular, kinetic and potential energies and their connection to motion) and pendulum motion. For the energy and motion topic, the students received a four-question pre-recitation homework and an in-recitation questionnaire. We designated nine of the 18 recitation sections as control sections (N = 164 out of 333 total), with the remaining nine sections receiving a choice of questionnaire format – our experiences with the first trial suggested that no asymmetry was necessary between the treatment and control group sizes. For the pendulum topic, we gave the students a recitation questionnaire only (no homework) in order to satisfy schedule constraints.

During data analysis, we restricted our attention to students who completed a homework (when there was a homework) and the corresponding questionnaire for a topic, which amounts to roughly 240 and 220 students for the first and second 102 topics, and 330 students for each of the two 101 topics.

Table 11.3 Percentage of students answering a homework problem correctly, sorted by representational format and topic

	Verbal (%)	Math (%)	Graphical (%)	Pictorial (%)
102 Diffraction/Interference HW (N = 241)	52	61	46	54
102 Bohr model HW (N = 218)	84	83	76	62
101 Mechanics/energy HW (N = 333)	54	70	50	49

Standard errors vary but are on the order of 2%

11.3.2 *Outcomes: Variation in Performance by Representation Use*

Our first research question simply asks whether variations in representational format on otherwise isomorphic tasks can lead to different performances. We examine the performance on both homework problems and questionnaires in various representational formats, but initially consider only the recitation questionnaires in the randomly-assigned format (control) group. The section following this one considers in detail the role of student choice of format and meta-representational competence.

Table 11.3 shows the percentage of students (in both choice and control sections) that answered each of the 12 homework problems (four formats in three different topics) correctly. The number of students in each subgroup appears in parentheses. In examining the homework data, we note that in several cases there were differences in performance from format to format on a particular assignment. When there was a difference in performance between two formats, the mathematical format was often one of the formats involved. The mathematical representation was the only format to require an explicit calculation. The other formats involved conceptual reasoning supported by descriptive language, graphs, or pictures – though successfully engaging in this reasoning should, in theory, involve at least a qualitative understanding of the pertinent mathematical formulae. We see that students were generally more successful with the mathematical homework format, which is consistent with the notion that first-year university physics students are more comfortable with ‘plug ‘n chug’ types of problems than with conceptual problems (Mazur 1996; Redish 2003).

We also see that there are some noticeable performance differences among the less-mathematical formats. For instance, consider the graphical and pictorial problems on the Bohr model assignment, shown in Fig. 11.2. Both require knowledge of how the electron orbit radius varies with the principal quantum number in the Bohr model. The questions differ only in which specific transition is being presented and in whether the problem and solutions are expressed in graphs or pictures/diagrams. Of the 218 students who answered both problems on the homework, 76% answered the graphical problem correctly and 62% answered the pictorial problem correctly. This difference is statistically significant ($p = 0.006$, two-tailed binomial proportion test) and is particularly interesting in that the graphical representation is a rather non-standard one. Students had not seen any graphs of orbital radius versus quantum number, but the pictorial representation of electron orbits should have been somewhat familiar since it is featured in both the textbook and the lectures that preceded this questionnaire. Further examination of the individual student answers on these two questions indicates that this performance difference can be attributed almost entirely to the 36 students who answered the graphical problem correctly and missed the pictorial problem by choosing the distractor C (Fig. 11.2). This distractor bears a strong resemblance to the canonical energy-level diagrams seen in the Bohr model section of the course's text and lectures. Since the problems are so similar and the same distractors are present in each problem, it appears that in this case representational variations may be traceable to a very topic-dependent cueing on visual features of one of the problems. This is essentially the WYSIWYG (what you see is what you get) cueing identified elsewhere (Elby 2000) when students often respond to superficial features of a representation, such as drawing a graph that looks like a hill when being asked to describe the kinematics of a car going over a hill.

Next, we examine the impact of representational format on student performance by looking at questionnaire performance amongst control group subjects (those randomly assigned one of four isomorphic problems that varied in their representational format). Consider the performance of these subjects on the mathematical formats of the 101 and 102 questionnaires. In three of the four questionnaires, the average success rate on the mathematics questionnaire was significantly lower than the average success rate on the other three formats combined. For the spectroscopy questionnaire, the average verbal/graph/pictorial score was 56% versus 13% on the math format, a difference significant at the $p = 0.004$ level. For the 101 spring questionnaire, the difference was 61% vs. 41% ($p = 0.03$), and for the 101 pendulum questionnaire, the difference was 62% vs. 30% ($p = 0.0004$). Note that students were generally less successful with the mathematical format on the spectroscopy questionnaire, in contrast to the earlier homework-based trials. We note also, however, that the mathematical representation of that particular questionnaire was difficult to solve through explicit calculation, and was more easily handled by using the equations qualitatively – a noteworthy example of how representational format can interact non-trivially with the contextual features and framing of a problem.

As with the homework analysis, we can find specific examples of performance variation across isomorphic problem presentations. The second 102 questionnaire deals with the emission spectrum of a Bohr-model hydrogen atom. The students were prompted to recall the spectrum of hydrogen, and were asked how that spectrum would change if the binding of the electron to the nucleus were weaker. The questions, answers, and distractors were as similar as possible on each questionnaire except for their representation.

Figure 11.3 shows the problem setups and one distractor for the verbal and pictorial formats of the spectroscopy questionnaire (performance data are in Table 11.4). Note that 1 week previous to the questionnaire, students completed a laboratory covering emission spectroscopy, and the questionnaire images match what students saw through simple physical spectrometers. Nineteen students in the control group

Spectroscopy Problem – Pictorial format
The Balmer series of spectral lines is shown below, below, as seen through a spectrometer:

Now suppose we are in a world where electric charges are weaker, so the electron is not held as tightly by the nucleus and the ionization energy is 13eV instead of 13.6 eV. Choose the picture that best represents what the new spectrum would look like.

B)

Spectroscopy Problem – Verbal format
Consider the Balmer series of spectral lines from hydrogen gas. Now suppose we are in a world where electric charges are weaker, so the electron is not held as tightly by the nucleus. This means that the ionization energy for the electrons will be smaller. What will happen to the Balmer lines that we see?

B) The spectral lines will all shift to shorter wavelengths (toward the bluer colors).

Fig. 11.3 Setup and second answer choice for the verbal and pictorial format questionnaires given in the second trial. The other distractors align between the different representational formats as well

Table 11.4 Questionnaire performance of students from the control (random-format) recitation sections

	Verbal	Math	Graphical	Pictorial
102 Diff.	24% (17)	56% (18)	25% (16)	58% (19)
102 Spec.	32% (13)	13% (15)	53% (17)	83% (18)
101 Springs	56% (43)	41% (39)	69% (42)	58% (40)
101 Pend.	55% (42)	30% (40)	64% (39)	67% (43)

Note: The number of students taking a questionnaire is in parentheses. The questionnaire topics are diffraction, spectroscopy, springs, and pendulums. Standard errors vary and are not shown, but are on the order of 2%

were randomly assigned a verbal format questionnaire, and 18 were randomly assigned a pictorial format questionnaire. 32% of the verbal group answered the question correctly, while 83% of the pictorial group answered correctly. This difference is significant ($p = 0.001$). Answer breakdowns indicate that eight of the ten students in the verbal group that missed the question chose the distractor corresponding to the spectral lines moving in the wrong direction (pictured in Fig. 11.3). Only one student from the pictorial group made this error. It is not clear why there would be such a split, especially since the pictorial format shows numerically larger wavelengths as being on the left, opposite the standard number line convention.

Table 11.5 Student performances on each of the study questionnaires, restricted to students that were given a choice of representational format

	Verbal	Math	Graphical	Pictorial
102 Diff.	35% (17)	37% (57)	4% (26)	82% (59)
102 Spec.	81% (21)	90% (42)	96% (27)	39% (58)
101 Springs	55% (11)	57% (102)	88% (17)	77% (39)
101 Pend.	62% (21)	39% (28)	65% (40)	78% (80)

Note: The number of students taking a questionnaire is in parentheses. Standard errors vary but are on the order of 2%

Table 11.6 Statistical significance of the questionnaire performance differences between the format choice and control groups in the 102 and 101 sections

Questionnaire subject	Verbal	Math	Graphical	Pictorial
102 Diffraction	***0.48***	0.16	0.04	***0.03***
102 Spectroscopy	***0.002***	***0.0001***	***0.0004***	0.001
101 Springs	0.95	***0.09***	***0.13***	***0.07***
101 Pendulums	***0.60***	***0.44***	***0.93***	***0.18***

Note: Numbers are p-values using a two-tailed binomial proportion test. Bold and italicized indicates that the treatment group (choice of format) had higher performance than the control group (random format). Note that the p-values shown do not include a multiple-comparisons correction; with such a correction, the Diffraction p-values can all be considered not significant

11.4 Outcomes: Role of Student Choice in Representations

Next, we address research question II: Can students productively assess and choose among different representations? Portions of each of the Physics 101 and 102 classes were allowed to choose the format in which they would take their recitation questionnaire. If students can accurately assess their abilities with different representations (or, alternatively, accurately assess the representation to which a particular topic is best suited), one might expect giving students this choice would improve their performance compared to a random assignment. In Table 11.5, we summarize the performance of the students who were given these choices, and also indicate the number of students that chose any particular format in parentheses.

Casual comparison of these data to those in Table 11.4 (the random-format, control group) immediately suggests that giving students a choice of format can impact student performance. In Table 11.6, we explicitly compare choice and control groups for a particular format and topic. There were a total of 16 choice/control comparisons available (four trials with four formats each). Of the eight from the 102 class, six showed a statistically significant difference, four of which (those involving the spectroscopy questionnaire) remained after applying a Bonferroni multiple-comparisons correction (Miller 1981). These data, along with the significances of the choice/control differences (or lack thereof) in the 101 class, are summarized in

Table 11.6. In every case, the null hypothesis is that student performance will be the same regardless of whether they are offered a choice of representational format.

These results are notable in that the effects are in some cases quite strong. For instance, 90% of the 42 students in the choice group answered the mathematics format question correctly for the spectroscopy topic, while 13% of the 15-student control group answered the same problem correctly. In addition, whether or not choice of format improves performance can vary. Table 11.6 shows four combinations of format and topic with strong treatment/control splits. In three of those giving students a choice of formats significantly increased performance, while in one case it resulted in a significant decrease. As we can see, giving students a choice of format does not result in consistently increased or consistently decreased performance relative to the control groups. This outcome suggests (without establishing conclusively) that these students do not have the meta-representational skills necessary to consistently make productive representational choices under these circumstances, and that a complete explanation of these performance differences will likely be non-trivial and will not be able to rely entirely on broad generalities. Factors impacting student performance in these circumstances, including the different pedagogical approaches and normative expectations in these classes, are further explored below.

Taken together, these results indicated that student performance on physics problems can indeed vary with representational format, often strongly. In the case of the Bohr-model homework problem, the performance difference between the nearly-isomorphic graphical and pictorial problems is likely due to students selecting a particular distractor. This distractor is one that superficially resembles energy-level diagrams that they have seen associated with this material, but only when it is represented pictorially. The data also begin to speak to the meta-representational skills (or lack thereof) of the students. Giving students a choice of format for a questionnaire did indeed result in performance differences as compared to the random-format students; however, the direction of that effect was inconsistent and not always positive.

11.5 Second Study Set: Creating Environments for Developing Representational Competence

The data from our early first set of studies led to our third research question. In particular, we noted that the effects of letting students choose problem representation was much more pronounced in the Physics 102 course than in the Physics 101 course. Was this qualitative difference in performance data a result of the different instructional style, the different content area, or some combination?

Table 11.7 Percentage of students answering a homework problem correctly, sorted by representational format and topic

Reformed Course, Replication Study	Verbal (%)	Math (%)	Graph (%)	Pictorial (%)
102 Diffraction/Interference HW (N = 332)	44	36	39	46
102 Spectroscopy/Bohr HW (N = 341)	63	60	55	48

Note: Standard errors vary but are on the order of 2%

Table 11.8 Questionnaire performance of students from the control (random-format) recitation sections (*top*) and from the treatment sections (choice of formats, *bottom*)

Reformed Course	Control group (N of random *assigned* format)			
Replication study	Verbal	Math	Graphical	Pictorial
102 Diffraction	19% (46)	35% (46)	14% (46)	18% (44)
102 Spectroscopy	59% (46)	39% (46)	57% (42)	54% (46)
102 Diffraction (dist)	33%	45%	44%	45%
Reformed Course	Treatment group (N of student in *choice* format)			
102 Diffraction	15% (16)	57% (34)	13% (37)	21% (77)
102 Spectroscopy	41% (17)	32% (25)	49% (37)	52% (89)
102 Diffraction (dist)	26%	22%	41%	32%

Note: The number of students taking a questionnaire is in parentheses. The questionnaire topics are diffraction and spectroscopy. Standard errors vary and are not shown. The last line indicates how many students chose a particular distractor on the diffraction questionnaire, as discussed in the text. None of the differences between treatment and control group performances were statistically significant

11.5.1 Accounting for Instructor/Instructional Approach

As we noted previously, these courses were taught by different professors and covered different material, and so the differences observed could conceivably be explained by differences in instruction, differences in content, or some combination. One possible explanation was that the much different approach of the reformed Physics 101 course resulted in students having a broader set of representational skills. Thus, whether or not they received their "preferred" representation made less of a difference (positive or negative) in performance (the X's in Table 11.6). The first part of this second study set begins to test that hypothesis by separating out the effect of instruction from the effect of content. We repeated the Physics 102 trial in the semester following the initial studies above, when the course was taught by the reformed-style professor who had been in charge of the Physics 101 course in the earlier studies. The trial was conducted in the same way, using the same homework and questionnaire problems, as the earlier Physics 102 trial. We predicted that given the same questionnaires, the choice/control splits would be much weaker than they were in the original trial with the traditional Physics 102 professor. As shown below, this prediction held true, leading us to analyze the specific differences in representation used in these classes in lectures, exams, and homework.

In Table 11.7, we see the performance of the reformed Physics 102 students on the pre-recitation homework. Notably, the percentage and statistical differences between the graphical and pictorial questions on the Bohr model homework (a key comparison in the previous study) are smaller than they were in the traditional Physics 102 course (55% vs. 48% instead of 77% vs. 62%, $p = 0.05$ vs. $p = 0.006$).

In Table 11.8, we see the performance of the students on the diffraction and spectroscopy recitation questionnaires, sorted by representation and by whether the students were in a treatment (format choice) or control group. Performance variation across representation was generally less statistically significant in this course than it was in the traditional Physics 102 section, including both questionnaires and homework. We also note here that the traditional students noticeably outperformed the reform students on the Physics 102 diffraction questionnaire. We suspect this result has to do with the relative emphasis on content in this version of the course. For the sake of replication, the exact questions from the questionnaire that were designed for the traditional Physics 102 course were given to the students in the reformed Physics 102 course, even though the reform professor did not emphasize this content as thoroughly.

The two Physics 102 courses placed different emphases on the different subtopics available, and the reformed section spent very little time on double finite-width slit diffraction. Student comments and performance suggest that most students treated this as a double infinitesimal-width slit problem. One of the distractors is correct for such an interpretation of the problem, and student selection of this distractor is noted in the (dist) line of Table 11.8 (performance is noticeably higher in most cases).

Analysis revealed that none of the treatment/control splits in this trial were statistically significant. That is, in the reformed Physics 102 course, student performance was not meaningfully affected by providing choice of representational format. Note that these data are essentially the same if one considers the correct diffraction questionnaire answer to be the distractor mentioned above. These null results are much closer in character to the results from the reformed Physics 101 course than the traditional Physics 102 course (in Table 11.6). This outcome suggests that the choice/control splits (or lack thereof) are associated more closely with the instructor and course environment than with the general content area – though very specific features of the topic and particular problem still matter. This finding motivated us to analyze these environments in more detail with the goal of identifying any differences in representational content and their uses.

11.5.2 Examining Course Structures: Cueing Representational Competence

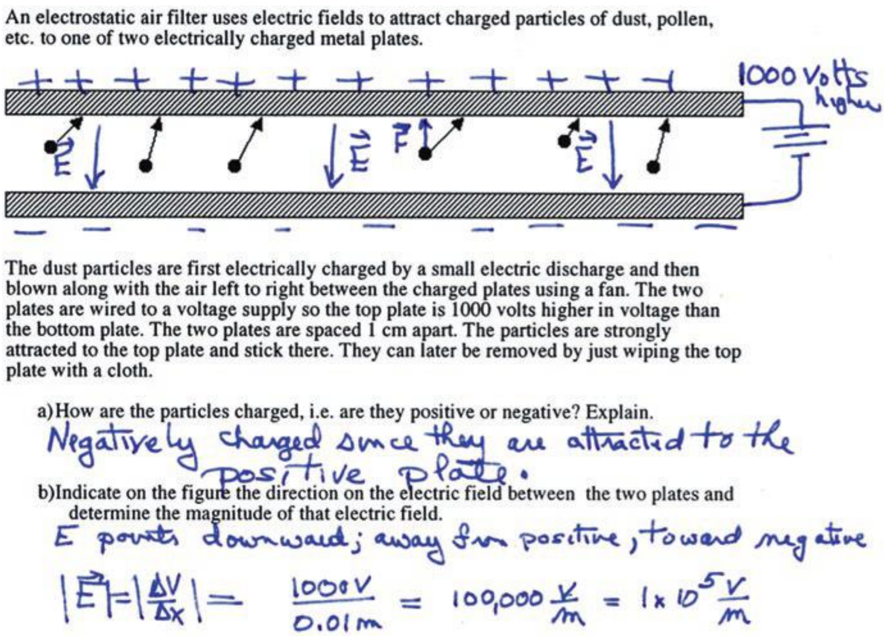
The courses under consideration (the reformed Physics 101, the traditional Physics 102, and the reformed Physics 102 courses) had many components, including lecture, laboratory/recitation, examinations, and homework. In comparing the courses, we judged the laboratories/recitations and homework to have very similar representational character. We thus focused our analysis on the lectures and examinations. This approach provided two views of the class. We saw how the use of physics representations was modeled for the students (the lectures), and how the students themselves were held responsible for using physics representations (examinations).

We videotaped several lectures from each of the three courses. The lectures covered the material probed by the questionnaires and some closely related material. We selected three lectures from each course for analysis, with each set of lectures spread over different topics, divided each tape into one-minute sections, and for each segment, noted which representations were used significantly according to the following rubric:

- Verbal: Writing sentences expressing an idea or concept on the board; presenting and explicitly referring to a slide with verbal-only content for the sake of the point at hand (words surrounding mathematics are not counted).
- Mathematical: Writing equations; explicitly referring to equations for the sake of the point at hand; doing mathematics. Writing numerical data by themselves is not counted
- Graphical: Drawing or modifying a graph; explicitly referring to a graph for the sake of the point at hand.
- Pictorial: Drawing or modifying a picture; explicitly referring to a picture for the sake of the point at hand.
- Physical demonstration: Carrying out a physical demonstration.

Note that for lectures, we have added the representational category “Physical demonstration.” Physical demonstrations can involve a number of representations (digital readouts vs. dials, for example), but we made no effort to further subdivide the category. We also noted which intervals include clicker questions. Finally, any interval in which more than one representation was used was additionally coded as a *Multiple Representations* interval (the Clicker category did not count towards this assignment).

Because the professor is speaking during nearly every part of a lecture, we did not count spoken words towards the use of verbal representations. This coding is an example of a broader feature of this study: the privileged position of the verbal representation. Essentially every aspect of the course had some verbal component (even math problems include explanatory text), and so we necessarily have stricter standards as to what counts as verbal representation use compared to the other categories.


An electrostatic air filter uses electric fields to attract charged particles of dust, pollen, etc. to one of two electrically charged metal plates.

The dust particles are first electrically charged by a small electric discharge and then blown along with the air left to right between the charged plates using a fan. The two plates are wired to a voltage supply so the top plate is 1000 volts higher in voltage than the bottom plate. The two plates are spaced 1 cm apart. The particles are strongly attracted to the top plate and stick there. They can later be removed by just wiping the top plate with a cloth.

a) How are the particles charged, i.e. are they positive or negative? Explain.

Negatively charged since they are attracted to the positive plate.

b) Indicate on the figure the direction on the electric field between the two plates and determine the magnitude of that electric field.

E points downward; away from positive, toward negative

$$|\vec{E}| = \left|\frac{\Delta V}{\Delta x}\right| = \frac{1000\,V}{0.01\,m} = 100{,}000\,\frac{V}{m} = 1 \times 10^5\,\frac{V}{m}$$

Fig. 11.4 Example exam problem with pictorial, mathematical, and verbal components. The problem is from a reformed Physics 102 exam, with a handwritten instructor solution

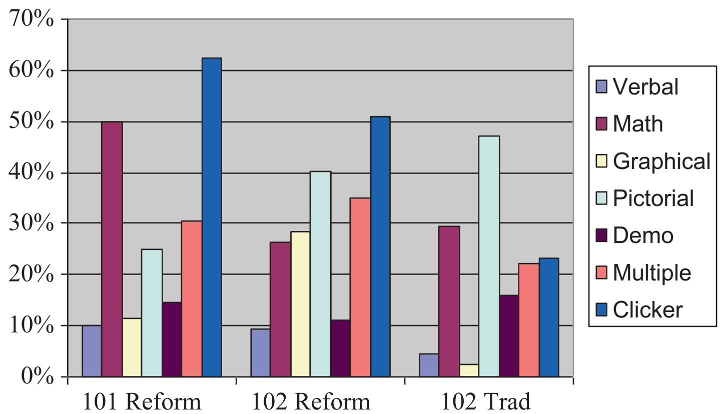


Fig. 11.5 Representational content of the lectures for the reformed Physics 101, reformed Physics 102, and traditional Physics 102 courses. "Multiple" category indicates use of multiple representations. "Clicker" category indicates percentage of class time involving questions that used a personal response system

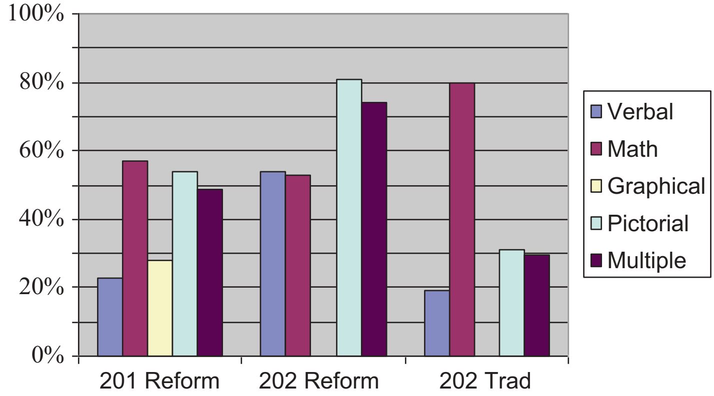


Fig. 11.6 Distribution of representations used in the exams in the three courses studied here. Also includes percentage of the exam problems that required explicit use of multiple representations

Once a lecture was coded, we calculated the percentage of the lecture that showed use of each of the representational categories. We then averaged across the three lectures from each class to obtain an average representational content for those courses' lectures. At least one lecture from each course was also coded by an independent researcher; inter-rater reliability was better than 90%.

Each of the three courses considered issued three mid-term examinations. We quantified the percentage of each exam that could be described as verbal, mathematical, graphical, and pictorial in representation using categories similar to those in the lecture analysis, with similar inter-rater reliability.

In Fig. 11.4, we see an example exam problem with the instructor's solution. In coding, we consider both the presentation of the problem and the required solution of the students. Part A of this problem was coded by the above standards to have verbal and pictorial components. Part B was coded to have mathematical and pictorial components.

In Fig. 11.5, we see the representational content in the reformed Physics 101, reformed 102, and traditional 102 lectures according to the standards described previously. Differences exist between all three sets, suggesting (not surprisingly) that both instructor and content have a significant effect on representation use. Most relevant to us is the comparison between the reformed and traditional sections of 102. The reformed section shows a broader selection of representations, with the verbal, math, graphical, and pictorial percentages summing to 104% vs. 83% in the traditional section. We also see more use of multiple representations (35% vs. 22%), and much more use of interactive clicker questions (51% vs. 23%).

In Fig. 11.6, we show the representational content of the exams in the reformed Physics 101, reformed Physics 102, and traditional Physics 102 courses. These data show the average across all exams in each course, excluding the final exam. We see the percentage of the exam problems (weighted according to their point value) that were verbal in nature, mathematical, graphical, and pictorial. We also see the percentage of the exam problems that required explicit use of multiple representations.

It is clear that the examinations from the reformed sections of Physics 101 and Physics 102 made use of a broader selection of representations than the traditional Physics 102 section. Perhaps most striking is the difference in the proportion of multiple-representations problems, with 49% for the reformed Physics 101 course and 74% for the reformed Physics 102 course versus 30% for the traditional course. The difference between the reformed Physics 102 and traditional Physics102 figures is statistically significant ($p < 0.0001$, two-tailed binomial proportion test).

To summarize, the reformed Physics 102 course shows choice/control performance splits (Table 11.8) that are much more consistent with the reformed Physics 101 data than with the traditional Physics 102 data. The course analysis data demonstrate that major components of the class (in particular the lectures and examinations) were strikingly different in how often representations were used in lecture and exams, with the reformed content being richer and using multiple representations more frequently. We thus tentatively conclude that these choice/control splits were associated more with instructional environment than course content area. The richer use of representations in-class is consistent with the notion that these students are learning a broader set of representational skills, which could explain the lack of choice/control splits. With this broader set of skills, working in a chosen representation as opposed to an assigned one could have less impact on performance.

We do not have evidence to claim that students in the reformed sections were necessarily learning better meta-representational skills (ability to choose between appropriate representation more effectively) than the students in the traditional section. It is quite conceivable that these students were no better than those in the traditional Physics 102 course at assessing their own abilities and evaluating the different representations available to them, but that their broader set of representational skills made any meta-representational failures less significant. Of course, neither do the data allow us to conclude that the reformed Physics 102 students were not learning better meta-representational skills.

11.6 Discussion and Conclusions

Depending upon one's perspective on the nature of knowledge and the nature of learning, one might consider that learning content may be independent of the representations used and the environments in which one is learning. Based on observation of common practices in introductory college physics courses, this may be the implicit theory upon which instructors act. Our courses, such as the traditional Phys 102 described here, do not specifically attend to student representation use, but often hold students accountable for working across varied representations. We, however, take a sociocultural perspective that holds human cognition to be a process mediated by artifacts and tools that take on meaning based on the environments in which humans find themselves. Courses that implicitly or explicitly teach students how to use representations, that both model and hold student accountable for such use, will develop students' capacities in working across representations, which are part of the physics content we seek for students to master. The studies described here begin to address whether and how students develop an ability to work across varying representations, whether students develop abilities to assess which representations they might most effectively use, and whether the variation of educational environment and instructional approach impact these outcomes.

In the first set of studies, where students solve isomorphic problems that vary by representational format, we find that students can exhibit dramatically different performances when working on problems that vary by representation. These variations appear to be coupled to both the specific content that is probed, and the environment (broader context) in which students are engaged. On the micro-scale, we find that students may be drawing from associated understandings of the questions at-hand. For example, we observe that students are likely mapping energy level representations to familiar pictorial representation of atomic radii in the Bohr model. If this is the case, such mapping can be unproductive and inappropriate. In other cases, it appears that students are drawing from appropriate representational maps, where students who have conducted in a laboratory in spectroscopy can appropriately map the observed phenomena correctly (perhaps recalling their own observations). Of course, to document these outcomes as causal would require continued studies, perhaps including interviews or focus groups to discern why students answer these questions the way they do.

In other instances, students may not be using the representations in the manner most productive for solving a problem. As an example, the use of mathematics in the spectroscopy questionnaire was better suited for qualitative rather than quantitative analyses. Students entering our introductory college physics classes may have developed a sense that mathematically represented problems are usually solved algorithmically and do not have a sense for reasoning conceptually with mathematics. It is likely that these issues of understanding the concepts/content, knowing the representational affordances, and knowing how to make productive use of different representations in different instances (an issue of meta-representational competence) are all at play and these first studies do not distinguish between these elements that influence student performance.

We follow up with studies that seek to clarify the role of working in a preferred representational format or not. We observe that there are differences in student performance when given a choice of representational format versus being assigned a problem in a given format; however the simple explanation that allowing students to work in the representation of choice would improve performance does not turn out to be the case. In some cases giving students choice of format improves performance, in some cases it decreases performance, and in other instance there is no impact.

Each of these outcomes associated with the micro-scale use of representations, suggests that more work should be done on developing students' meta-representational skills. If students understand better the key attributes and affordances of representations and how these are associated with given content areas, they will better be able to productively deploy these representational tools during problem solving. One promising approach to such an end may be to make use of analogical maps to link representations and content areas (Podolefsky and Finkelstein 2006, 2007a, b). Earlier work suggests that teaching students to blend representations in carefully scaffolded ways might allow a productive understanding of representations in one content domain (e.g. sine waves with sound) to be used in another (sine waves with electromagnetic radiation). All told, findings here and elsewhere suggest that it is fruitful to teach representational competence in a contextualized (content-bound) manner.

At the more macro scale, in the studies comparing students working within assigned representational format versus a chosen representational format, there was a strong suggestion that the instructional environment mattered. A class that was reformed, using more interactive engagement techniques (Phys 101) appeared not to show meaningful splits between the assigned (control) and the choice (treatment) group, whereas the traditional class does. It is possible that students are developing some broader representational competence (a mastery of domain in a way to allow moving across representational formats) in the reformed course, however the mechanism behind such development is unclear.

In the second set of studies, we find that the teaching of such representational competence need not be part of the explicit agenda. Providing opportunities for students to practice the use of coordinated representations, even without explicit training, appears to improve students' performance. We note that we can characterize classes differently based on how many different and multiple forms of representations are used in the lectures (environments that model representation use) and examinations (tasks that hold students accountable for representation use). Of the classes studied, the one that provides richer modeling of representation use also featured less variation in performance with representation and no apparent difference in performance based on whether students are working in a preferred format. It is unclear at this time whether this effect was due to some developed meta-representational skills, increased representational competence across formats, or something else altogether. It is entirely possible that students in the reformed class may be no better or worse at assessing their own understanding of representations. It would be appropriate to investigate this in follow-up research, replicating the sorts of studies conducted here while also having students explicitly describe the utility of different representations and predict their abilities to work in varied representations. Going forward, understanding the practices that allow us to intentionally build up student meta-representational competence will be a productive area for further study.

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Chapter 12
The Role of Representations in Students' Explanations of Four Phenomena in Physics: Dynamics, Thermal Physics, Electromagnetic Induction and Superposition

Jennifer Yeo and John K. Gilbert

12.1 Background

Scientific explanations are "accounts that link scientific theory with specific observations or phenomena" (National Research Council 2012). Representations play a vital role in the explanations of natural phenomena that physics, and indeed the other sciences, provides. Text, mathematical symbols, graphs, pictures and even gestures are some of the common types of representation used to inscribe scientific theories and laws as explanations are produced and communicated. Such representations can be conceived as acts of imagination by their creator (Gilbert 2005) as Gooding (2004) and Nersessian (1992) have shown in respect of Michael Faraday's extensive use of images in his conceptualisation of magnetic fields and his explanation of the electric motor. The use of representations can be considered as a crucial epistemic practice by the scientific community.

The desire to make science education as 'authentic' as possible (Roth 1995) leads, by analogy, to the assumption that the use of representations is central to the understanding of established science. Indeed, the theory of learning enshrined in 'constructivism' (e.g. Vygotsky 1978), sees considerable parallels between science and science education. Like scientists, students need to use representations as instruments to consider their action on other objects (e.g., the interaction of magnetic fields). These representations thus function like real objects, whose behaviour draws on parallels with our daily experiences (e.g., the general belief that "more' anything

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is 'stronger"). In other words students will use representations as a way of accessing and deploying their explanatory intuitions.

We know very little about students' use of representations in the construction of scientific explanations, in particular the range of representational competencies that students need in order to produce a scientifically-acceptable explanation. Although work has been done into students' construction of explanations (e.g. Campbell et al. 2011; Tytler et al. 2013a; Yeo and Gilbert 2014), research has historically concentrated on the provision of explanations by teachers (e.g. Ogborn et al. 1996). With the capability of producing explanations being one of the primary objectives in many science curricula (e.g., Ministry of Education 2015; National Research Council 2012), it is paramount that teachers become aware of how students themselves go about producing explanations of phenomena. Such knowledge should inform teaching strategies that include the use of multiple representations. In order to redress this balance of emphasis, the aim of this chapter is to present the natures of 'successful' students' representational capabilities when constructing explanations across four classes of phenomena in physics – dynamics, superposition, thermal physics and electromagnetic induction, chosen as representatives of the major themes in physics curriculum.

12.2 Theoretical Framework

In order to address this task, we need a universally acceptable way of talking about 'explanations'. Yeo and Gilbert (2014) set out such a framework for an 'explanation of explanation', consisting of three dimensions ('function', 'form', and 'level'). In this section, we set out its manifestation in scientific explanations in physics. This will enable us to show how they relate to the different aspects of producing scientific explanations and how representations enter into them.

12.2.1 Function

The function of a scientific explanation is to give an answer to specific types of question. Gilbert et al. (2000) proposed a six-element typology of explanations, based on the type of questions addressed (see Table 12.1). The different types of scientific explanation, each serving a different function, imply that various explanations can possibly be produced for a given phenomenon. Students need to recognize the purpose and/or context in which the responses are sought in order to participate meaningfully and effectively in scientific discourse.

The nature of physics, consisting of scientific laws (e.g., Newton's laws, Gas laws, Ohm's law) and theories (e.g., kinetic theory of matter, wave theory, field theory), suggests that interpretive and causal explanations are important types of explanations in physics.

Table 12.1 Typology of scientific explanations

Types of explanation	Purpose	Question answered
Contextualizing	Gives a phenomenon a name, an identity, and enables it to be treated linguistically as a noun	What exactly is being investigated?
Intentional	Epistemological explanation – provides a reason why a phenomenon is being enquired into and its importance	Why should a particular phenomenon be investigated?
Descriptive	States the nature of and typical values for its physical properties	What are the properties of a phenomenon?
Interpretive	States and describes the model that can be used to think about the properties of the phenomenon	What models can be used to think about the phenomenon?
Causal	States how the postulated model is thought to produce the observed behavior by the operation of 'cause-and-effect' mechanisms	Why does the phenomenon behave as it does?
Predictive	Concerned with convincing others of its degree of validity (justification) or ability to produce predictions	How will the phenomenon behave under other, specified, circumstances?

From Gilbert et al. (2000)

12.2.2 Form

The *form* of a scientific explanation refers to its structural organisation. Borrowing this notion from linguistics, it identifies how the different elements of an explanation are put together into a whole. By analysing written explanations in science, Veel (1997) found five different types of explanatory organisations to be commonly used in science. For example, a causal explanation involves the identification of the phenomenon followed by a description of a number of cause-effect phases, while a law-based explanation involves a statement of principle followed by an elaboration of that principle as used to explain the events that happen. These organisations are not merely structural frameworks to make the construction of meanings apparent to a reader or listener, they are also reflections of the meaning-maker's thought processes as meanings are being produced, extended and put together as a coherent whole.

12.2.3 Level

The *level* of a scientific explanation can be thought of in three ways, in terms of its: precision, abstractness and complexity.

Level of Precision Over the course of the history of science, scientists develop explanatory models to account for phenomena observed. Models are representation of a system built up with interactive parts using representations of those interactions.

The models that scientists developed are (inevitably) known as scientific models (Crawford and Cullin 2004). There are many types of scientific models – scale models, analogue models, theoretical models, and mathematical models (Black 1962). In any field of enquiry, one model is succeeded by another by virtue of its ability to account for a broader range of phenomena. For example, each successive version of the model of the atom was able to account for more phenomena, hence increasing the level of precision that was possible. In school, students might learn an earlier model rather than a more precise later model. It is not so much the case that they are learning the "wrong" model, but rather that their explanatory capabilities are limited to the scope of phenomena they would be expected to encounter at that grade level. Students producing a scientific explanation need to select an appropriate scientific model to make use of in building a suitably precise account of the behaviour of a phenomenon.

Level of Complexity A scientific explanation needs to be convincing to the questioner who seeks it, whether it is oneself or others: it must be complete and coherent. Explanations are considered suitably complete when all relevant entities and processes attributing to the phenomenon are accounted for and the reasons for the claims made are provided. Their coherence depends on the extent to which scientific knowledge has been applied in ways acceptable by the scientific community.

Level of Abstractness Physics, and therefore the nature of scientific explanation in physics, is known to be notoriously abstract. The above features of scientific explanation (function, form, precision, and complexity) all invoke a meaning-making process in which representations are indispensable. Different types of explanatory model are inscribed using different forms of representation. Thus in detailing the underlying mechanism that produces an effect, entities that are not visible or may not physically be in existence are constructed. These constructs are reified in some way by means of a signifier or representation. For example, pictorial arrows are used to represent magnetic fields and magnetic field strengths, while symbols like V, I and R are used to signify potential difference, current, and resistance respectively. In doing so they act as an aide to thinking and reasoning about the events and processes taking place (Nersessian 1992; Tytler et al. 2013b; Yeo and Gilbert 2014). Representations are thus vital resources in the construction of an explanation in physics.

This central resource for meaning-making and the role of representations in mediating the construction of scientific explanation are not well-understood. While there exists some studies that looked at how students learn with different forms of representations (e.g., Reiner 2009; Tytler et al. 2013a; Won et al. 2014) they generally do not examine the roles played by different forms of representations in mediating thinking and reasoning when students produce scientific explanations. Thus, this study aims to identify the natures of the representational capabilities that are the hallmark of students who are 'successful' when constructing acceptable explanations across four classes of phenomena in physics – dynamics, thermal physics, superposition, and electromagnetic induction. In order to understand how representations are used in different types of explanations for these four classes of phenomena, our research questions were:

1. What types of explanations (function) were produced for each of the four phenomena when students were asked to 'explain' them?
2. How did students go about producing them (form)?
3. What representations were used and how (level of abstractness)?

By 'successful explanation', we refer to those that were based on a relevant scientific model, complete with evidence and justification, and where the premises were used in a scientifically consistent manner.

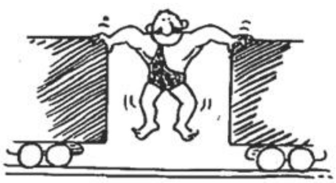
12.3 Research Method

This study is part of a larger mixed method study to identify the characteristics of explanation in physics produced by high school students, and the difficulties students face with producing scientific explanations. This is the qualitative part of the study whereby a case study approach is used to identify the characteristics of 'successful' scientific explanations produced by high school students (Grades 11 and 12), with the aim that these characteristics can be used to code a larger set of explanations produced by students and confirmed, and difficulties students have in producing scientific explanations identified.

Think-aloud interviews were conducted on different topics with Grades 11 and 12 students in Singapore in order to understand the process of constructing a scientific explanation. A total of four topics – dynamics, thermal physics, superposition and electromagnetic induction – were chosen as representative of the main themes in high school physics curriculum. These are also topics that students found difficult, hence understanding what it takes to produce an explanation in each of the topic can perhaps explain some of the difficulties students face for each of the topic as well. As part of the larger study, approximately 80 students from four different high schools were interviewed on each topic, hence generating a total of 275 explanations. The explanations constructed were categorised as 'successful' or 'unsuccessful', as expected at that Grade level by a former physics teacher and a physics graduate. One explanation that was representative of the 'successful' explanations for each topic was then selected for in-depth analysis and comparison between them.

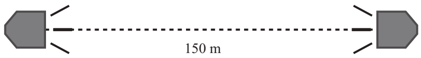
Each think-aloud interview consisted of one phenomenon based on the abovementioned topic being presented to the student. Figure 12.1 shows the phenomena. For each phenomenon, the students were asked to explain the observations, though the task might be phrased differently. In presenting the probes, we were mindful of the need to communicate the phenomenon clearly. While the probes were mostly presented in written text, accompanying diagrams were included to ensure clarity. For the phenomenon on electromagnetic induction, it was presented as a

The strongman will push the two initially stationary freight cars of equal mass apart before he himself drops straight to the ground. He found that he was unable to give either car a greater speed than the other. Explain the phenomenon.



Probe A: A Dynamics Phenomenon

John is standing in between two loudspeakers facing each other. They are spaced 150 m apart. Both loudspeakers play a sound of the same pitch and loudness continuously. As John walks from one loudspeaker to the other, he realizes that he cannot hear anything coming from the loudspeakers at 5 specific positions. At some other positions, it is especially loud. Explain the phenomenon.



Probe B: A Superposition Phenomenon

A bicycle pump is connected to a bicycle tire and pumped rapidly many times. Explain why the air in the pump becomes hotter after a while. The bicycle pump is insulated.

Probe C: A Thermal Physics Phenomenon

Why does the magnet take a shorter time to fall through the copper tube than the plastic tube?

Probe D: An EMI Phenomenon

Fig. 12.1 The four probes used for think-aloud interviews demonstration to ensure brevity of words without compromising the clarity of ideas communicated.

These interviews were conducted after the students were taught the topic. As the students came from different schools that had different teaching timeline, there was no fixed interval between the interviews. During the interviews, the student could verbalise their explanation or write out the explanation. He/she could also draw, use gestures, or any other modes of representation, to produce the explanation. Writing and drawing materials were available for the students' use. In addition, we also provided waveforms drawn on transparencies for the superposition phenomenon because papers were not good medium for superimposing one wave over another. However, the use of these tools was not prescribed at any point during the interview. Each explanation took approximately 10 min. For the selected explanations, there were few interruptions from the interviewer except for clarification purposes. Each explanation was video-taped, with a focus on the students' talk, drawing and gestures. A multimodal transcript of each interview was generated according to the conventions of Kress et al. (2001). Analysis followed Lemke's multimodal framework – presentational, organisational and orientational (Lemke 1998), to identify the characteristics of the explanation according to our explanatory model. The presentational dimension examines the content presented (e.g., events, actions, description); the organisational dimension examines how this content is built up, and the orientational dimension examines the representations used in constructing the explanations. These dimensions thus inform the function and levels of precision and complexity, the form and the abstractness of a scientific explanation respectively. Put together, the analysis framework produced answers to the three research questions.

12.4 Findings

12.4.1 Response to Research Question 1: What Types of Explanations Were Produced for Each of the Four Phenomena When Students Were Asked to 'Explain' Them?

We found two main types of explanations produced among the four phenomena – 'interpretive' and 'causal'. The phrase 'Explain the phenomenon' was evidently interpreted by the interviewees in just one of these two ways. We considered the explanations produced for the topics of dynamics and thermal physics to be interpretive. Figures 12.2 and 12.3 show excerpts of the explanations for these two topics.

In Figs. 12.2 and 12.3, the explanations of dynamics and thermal physics were constructed based on Newton's laws and first law of thermodynamics respectively. In constructing these law-based explanations, the laws, which are often expressed in mathematical equations, were interpreted in the context of the phenomena presented.

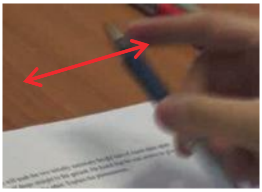
Turn	Explanation in textual form	Explanation in other forms of representation	Specific behavior
26	Because.. According to Newton's law, …		Name rule (Newton's law)
	because he's connected to both suitcase,	 Points to the two cars	Identify state of objects
28	the man push this car	 Draws an arrow pointing leftward on the man's hand on the left	
	so the car would give him an equal force but in the opposite direction..	 Draws an arrow pointing rightward on the man's hand on the left	Conclude the action of car on man and state the quantitative and spatial relationship of man on car.
34	he doesn't move ( ) means the net horizontal force must be zero	 Moves pen left to right horizontally	Identify the state objects, and state of a generalised rule (Newton's first law)

Fig. 12.2 Excerpt of explanation of dynamics

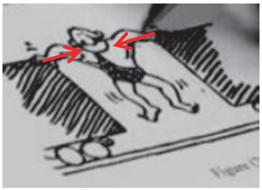
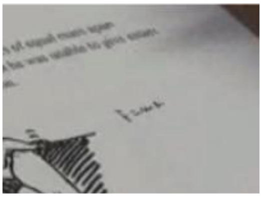
	so only these two force is equal	 Points to the arrows pointing to the man	Conclude the quantitative properties of forces on man
	so hence the force he exert on these two cars are equal	 Points to the arrows pointing to the cars	Conclude the quantitative relationship between forces
	and so the cars are of equal mass		Identify the quantitative properties of cars
	so F=ma	 Writes down equation, F=ma	State mathematical equation of Newton's second law
	so their acceleration are equal		Conclude quantitative property of "a"
	so the speed will be equal cos stationary.		Conclude the quantitative property of v, identify initial state of cars

Fig. 12.2 (continued)

For example, in the explanation of dynamics, the interpretation of "F = ma" entails the identification of each of the variables in the phenomenon (Fig. 12.2, Turn 34). Likewise, the explanation of thermal physics, based on the mathematical equation "U = W + Q", involved identifying the quantitative properties of each variable in the given context (Fig. 12.3). These explanations, which involved stating a mathematical model and describing the properties of its components, were thus considered to be 'interpretive', in accordance to Table 12.1. As the models used here are law-based,

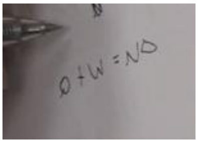
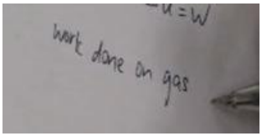
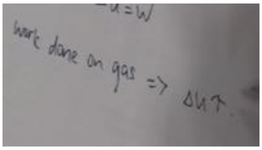
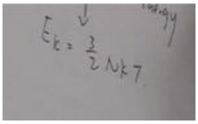
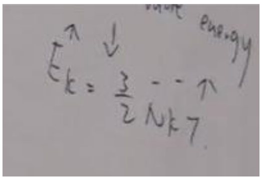
Turn	Explanation in textual form	Explanation in other forms of representation	Specific behavior
8	U equals to W plus Q.		State first law of thermodynamics
	Q equals zero.		Identify the quantitative properties of Q
12	… Because it's pumped. work done on the gas.	 Writes "work done on gas"	Identify the process of system, infer quantitative property of W
	That means internal energy go up. …	 Adds an arrow towards ΔU increase	Conclude qualitative property of U
18	Energy … Ek = 3/2 NkT		State the mathematical relationship between E_k and T.
	so increase in energy and the particle remains the same, k the same then temperature will go up."	 Adds arrows/line against each variable added	Identify quantitative properties of E_k, N and k, conclude how temperature changes.

Fig. 12.3 Excerpt of explanation of thermal physics

it suggests that interpretive explanations tend to be based on scientific laws in physics. As there are many laws in physics, it is to be expected that learning to produce interpretive explanations would be a key focus in learning to produce explanations in that subject.

Unlike the law-based explanations observed in Figs. 12.2 and 12.3, Figs. 12.4 and 12.5 are based on theories of physics. Figure 12.4, an explanation of electromagnetic induction, is based on field theory, which assumes the presence of magnetic fields produced by a moving electron and a magnet, and their interaction when they

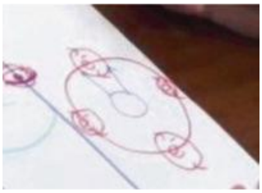
Turn	Explanation in textual form	Explanation in other forms of multimodal	Specific behavior
91	Top view	 Draws circle	Decide on the orientation, spatial perspective to take of the phenomenon
	… we have … the magnet here, north pointing downwards actually	 Draws a smaller circle	Identify objects of phenomenon and their spatial properties
	So … there is the electron … view from the top,	 Curls finger clockwise	Identify the presence of microscopic entity (electron), and decide on the orientation, spatial perspective Use of scientific rule (Right hand grip rule)
	clockwise	 Draws clockwise arrows around "e⁻"	Identify the inferred entity (magnetic field); reify the magnetic fields and their spatial properties and relationship with other objects
	The magnet is actually small. …		Identify the object in phenomenon (magnet) and its property (small)
	It actually curves upwards. So … curving this way	 Draws two arrows from the circle in the middle	Identify the presence of magnetic field; reify the inferred entity and its spatial properties in pictorial form

Fig. 12.4 Excerpt of explanation of electromagnetic induction

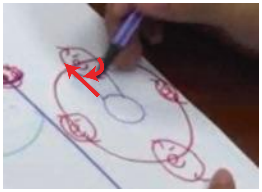
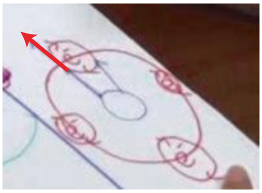
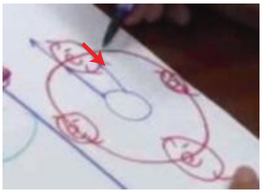
	Magnetic field lines … you can actually add them together like vectors		Identify how the entities (magnetic field) will interact
	So when these two magnetic field interact,	 Points to the two arrows (bolded)	Identify the entities that would interact
	This direction will be stronger, this direction will be weaker …	 Draws arrow pointing upwards (bolded)  Draws arrow pointing downwards (bolded)	Conclude the result of the interaction between the entities

Fig. 12.4 (continued)

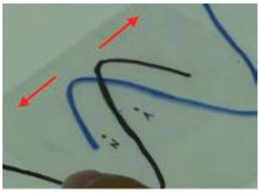
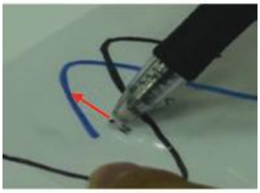
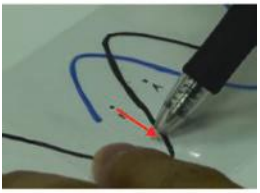
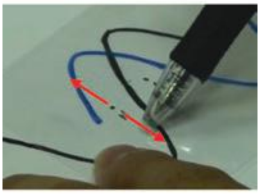
Turn	Explanation in textual form	Explanation in other forms of multimodal	Specific behavior
21	and as they go on again,	 Moves waveform apart	Identify the behavior of waves at a particular time
	the length ... the amplitude from here is the same	 Moves pen upwards	Identify the quantitative properties of the waves at a particular node.
	as the amplitude from here.	 Moves pen downwards	
	So these 2 amplitudes will cancel out each other	 Moves pen upwards and downwards	Describe the action of the waves on each other at the node.
	so it will still be zero.	 Points to the dot labelled "N"	Conclude the result of the interaction between the two waves at the antinode of the
29	… so it is a stationary wave		Identify the name of the phenomenon

Fig. 12.5 Excerpt of explanation of superposition

come together in the same area. Likewise, the explanation of superposition (Fig. 12.5) is based on wave theory that assumes the presence of energy in the form of waves that can "cancel out each other" (Turn 21) or add up when they meet to produce a new waveform. These causal explanations bore characteristics of cause-effect mechanisms (agent-target pair) that Lakoff and Johnson (1980) identified as features of causality, and hence are categorised as causal explanations. These theory-based explanations suggest that causal explanations are based on scientific theories in physics.

12.4.2 Response to Research Question 2: How Did Students Go About Producing Them?

The process by which the explanation of each identified type of explanation was produced are shown in Tables 12.2 and 12.3. Based on the categorisation of the types of explanations for each of the phenomena, we have grouped the explanations of dynamics and thermal physics in Table 12.2, and the list of construction behaviour for electromagnetic induction and superposition are in Table 12.3. To further clarify the organisation of the tables, columns 1 and 5 of each table show the specific behaviour exhibited by the students for each phenomenon, while columns 2 and 4 summarise the behaviours in more general terms. Column 3 lists the common behaviours observed of the type of explanation produced, as derived from the common behaviours observed. These specific behaviours indicate the style of reasoning of each student, and, when compared, the list of common behaviours is an indication of the style of reasoning for the type of explanation. However, it should be noted that the lists of behaviours need not necessarily mean that they have to be produced sequentially: they just represent a list of behaviours observed in producing that particular type of explanation.

The process of producing the interpretive explanations on Dynamics and Thermal Physics (refer to Table 12.2) shows some common behaviours identified from the two explanations. While an interpretive explanation is largely dependent on scientific laws, which are commonly expressed mathematically, its deployment goes beyond mathematical computation. Instead, it involves (1) reconstructing the physical system to produce a mathematical model by identifying key aspects (objects, actions and processes) of the phenomenon (e.g., man push car), inferring the presence of abstract entities (e.g., car will give him an equal 'force') based on these key aspects of the phenomenon and scientific laws, and deducing the quantitative properties of these inferred entities (e.g., these two forces are equal) from scientific laws (e.g., Newton's first law), (2) relating these physical quantities with a mathematical equation (e.g., $F = ma$), and (3) computing the variables to generate a quantitative outcome. This quantitative outcome will then need to be interpreted in the context of the physical system (e.g., "The speed will be equal"). We see a similar reasoning

Table 12.2 Process of producing interpretive explanations of dynamics and thermal physics

Explanation of dynamics		Common behaviors of interpretive explanations	Explanation of thermal physics	
Specific behaviors	General behaviors		General behaviors	Specific behaviors
1. State Newton law (N3 L)	Establishing the existence and quantitative relationship between two inferred entities (forces on the cars), which entails:	Identify key aspects/state of the phenomenon (objects, behavior, and/or processes)	Simplify the process of the phenomenon	1. State assumption (one rapid pumping)
2. Identify state of objects (man and car were connected)	(a) Identify the key aspects of phenomenon (objects, properties and behaviors)	Identify presence of inferred entities based on the state of the phenomenon		2. Identify the state of phenomenon (it is a rapid process)
3. Identify action of man on car and its spatial properties	(b) Identify the presence of inferred entities (based on the behaviors or properties of the objects or processes of the phenomenon)	Infer the quantitative properties of the inferred entities, justified by scientific laws, rules and principles, knowledge		3. Infer qualitative behavior of heat (heat does not leave or enter); identify the presence of heat
4. Identify presence of inferred entity (force) and its spatial properties (direction and location)	(c) Identify the quantitative properties of inferred entities based on scientific laws	Identify a mathematical model that applies to the state of the phenomenon and relate the observation to other inferred entities	Identify a mathematical model that applies to the phenomenon, that relates the inferred entities to the observation to be explained	4. State $U = W + Q$
5. Conclude the action the car on man ("exerts a force"), and state the quantitative and spatial relationship with the force by man on car		Perform mathematical operations to arrive at the quantitative property of the unknown variable in the mathematical equation	Establish the existence and quantitative property of inferred entities, which entails:	5. State quantitative property of Q
6. Name Newton law (wrongly identified as N3 L)		Conclude the quantitative property of the unknown variable	(a) Identifying the key aspects of the phenomenon (processes, action)	6. Identify the presence of work done (reason) as reason

(continued)

Table 12.2 (continued)

Explanation of dynamics		Common behaviors of interpretive explanations	Explanation of thermal physics	
Specific behaviors	General behaviors		General behaviors	Specific behaviors
7. Identify the state of object (man's horizontal position has no change)		Relate the quantitative property of the unknown variable to the observation made	(b) State the presence of inferred entities and infer their behaviors based on the processes and actions.	7. State the process of the system (it's pumped) as reason
8. State N1 L as relevant to the context (the net horizontal forces are equal)				8. Infer qualitative property of W based on reasons in point 6 and 7
9. Conclude the quantitative relationship between forces (inferred entities)			By mathematical operations, conclude the quantitative property of the unknown variable	9. Conclude qualitative property of U
10. State mathematical equation for N2 L (F = ma)			Identify a mathematical model that applies to the phenomenon, that relates the inferred entities to the observation to be explained	10. State Ek = NkT
11. Identify the quantitative property of the mass of the two cars	Identify a mathematical model that applies to the phenomenon, that relates the inferred entities to the observation to be explained		Establish the existence and quantitative property of inferred entities	11. Identify the quantitative properties of Ek, N and k, with reasons (particles remains the same)
12. Conclude quantitative property of a	Identify the quantitative properties of the variables in the mathematical model		By mathematical operations, conclude the quantitative property of the unknown variable	12. Conclude how temperature changes (will go up)
13. Conclude quantitative property of v.	By mathematical operations, conclude the unknown variable		Relate the mathematical quantity to the physical phenomenon	13. Connect change in T (temperature will go up) to the sense (feels warm to touch)
14. State the initial speed of car (reason for why v are the same?)	Identify the state (behavior) of the phenomenon and conclude the quantitative property of the physical quantity (speed)			

Table 12.3 Process of producing causal explanations of phenomenona of electromagnetic induction and superposition

Electromagnetic induction		Common behaviors of causal explanations	Superposition	
Specific behaviors	General behaviors		General behaviors	Specific behaviors
1. Identify the objects and their spatial properties	Simplify phenomenon	Simplify phenomenon – key aspects of the phenomenon	Simplify phenomenon	1. Identify key characteristics of the phenomenon (same pitch)
2. Decide on the orientation, spatial perspective to take of the phenomenon and its relationship		Identify presence of inferred entities (magnetic fields, waves), and their properties and reify them to produce an analytical structure	Identify properties of sound (freq, amplitude and speed)	2. Identify properties of physical quantities related to sound (freq, amplitude, speed) of the two waves
3. Identify the presence of inferred entities (magnetic field) and microscopic entities (electrons) based on the nature and properties of the objects in the phenomenon	Identify inferred entities and their properties to produce an analytical structure	State the behavior of one entity on another entity, based on rules and scientific knowledge	Identify the name of the phenomenon	3. Identify the name of the phenomenon – standing wave (or the inferred entity responsible for the phenomenon), and the presence of nodes and antinodes
4. Reify the inferred entities and the microscopic entities, and their spatial properties and relationship using pictorial representations, based on scientific rules (right hand grip rule) and knowledge (magnetic field around a magnet)		Using the analytical structure, identify the action of one entity on another at different (key) time interval and at different (key) positions/locations	Produce an analytical structure based on the properties of sound (two sinusoidal waves orientated with a phase difference of 180 degrees, mark out two points along the path of waves, specific point intervals to discuss the wave)	4. Reify the presence of inferred entity with the institutionalized rep of it - wave

(continued)

Table 12.3 (continued)

Electromagnetic induction		Common behaviors of causal explanations	Superposition	
Specific behaviors	General behaviors		General behaviors	Specific behaviors
5. Identify how the entities would interact with each other (magnetic fields of magnet and electrons acting like vectors which can add or cancel each other)	Using the analytical structure produced, state the actions of one entity on another and the result produced.	Conclude with the effect of the action of one entity on another at any time interval and location Relate the effect on the inferred entity on the physical object or observation made.		5. Orientate the two waves to represent the characteristics (coherent but opposite direction)
6. Conclude the result of the interaction between the entities (unbalanced magnetic field)				6. Identify the behavior of the waves (move towards each other)
7. Identify how outcome (resultant magnetic field) would produce another effect as it acts on another entity in the phenomenon (electron) – electron made to move	Using the same analytical structure, describe how an earlier effect acts on existing entities to produce another effect			7. Mark out the nodes and antinodes of the stationary wave
8. Identify the presence of new entity (induced current and a magnetic field produced) resulting from the effect produced earlier and based on scientific rules and knowledge	Identify and reify presence of new entities resulting from the new effect, to transform the analytical structure		Using the analytical structure, identify the action of one wave on another and the effect, based on mathematical rules, at specific points along the wave	8. Describe the action of the waves on each other at different time when the displacement between the two waves are = 0, ¼ l, 1/2 l, 3/4 l, l
9. Reify the presence of the new entity				9. Conclude the result of the interaction between the two waves at the node and antinode, at different time interval – shape of wave changes, amplitude of wave changes

10. Identify how the new entity would interact with the existing entities (magnetic field of the magnet) based on rules	Using the new analytical structure, state the action of the new entity on other existing entity, based on mathematical rules			
11. Conclude the effect of the interaction (magnetic field)				
12. Identify how the effect of the interaction would affect the physical object of the phenomenon	Relate the effect back onto the physical system			

process with the explanation of thermal physics though the number of physical objects and processes was fewer than that of dynamics.

Table 12.3 shows the list of behaviours for producing the causal explanations of electromagnetic induction and superposition, which bears some key differences with that of the interpretive explanations. Its production entailed the identification of the key aspects of the physical phenomenon (e.g., magnet, copper tube, positions of magnet with respect to copper tube), inferring the presence of abstract entities, which were given some physical form and properties (e.g, arrows for shape and direction of magnetic field), and description of the events produced by the action of one entity on another. These actions were then justified by a statement of scientific or mathematical rules (as opposed to laws) that prescribed how the entities could act on one another. For example, in Fig. 12.4, the vector rule "magnetic field lines … you can actually add them together like vectors" was used to determine how magnetic fields. In Fig. 12.5, the behavior "these 2 amplitudes will cancel out each other" was used to define how the waves would behave when they 'meet'.

Comparing the processes of producing the interpretive and causal explanations, we can identify similarities, yet differences in their construction. We see that while both types of explanations involved the reconstruction of the physical phenomenon with abstract entities so as to produce an analytical structure for reasoning about the phenomenon to take place, the kinds of analytical structure produced for either type of explanations are different. For the interpretive explanations, these inferred entities were turned into mathematical symbols and related mathematically to each other. Reasoning about the entities is thus mediated by mathematical algorithmic rules in order to deduce their outcomes. For the causal explanations, inferred entities were turned into a pictorial form so that the actions of one entity on another could be thought about in a qualitative and physical way. In that sense, an interpretive explanation made up of attributes and properties of entities can be considered to have a descriptive structure, while a causal explanation made up of a sequence of events taking place tends to be narrative. The differences between the generic organisations are indications that the styles of reasoning for the two types of explanations are different.

12.4.3 Response to Research Question 3: What Representations Were Used and How?

In respect to the first two research questions, we found two main types of explanations produced by students and that each type of explanation entailed a different reasoning style. In this third research question, we report how representations mediated their construction. To this end, Tables 12.4 and 12.5 summarise the conceptions (columns 2 and 4 for each phenomenon) and the types and function of representations used (columns 3 and 5) for the behaviours of each type of explanation.

Table 12.4 Representational behaviours observed of producing interpretive explanations of phenomena of dynamics and thermal physics

	Dynamics		Thermal physics	
General behaviors	Conception	Representations	Conception	Representations
1. Identify key aspects/state of the phenomenon (objects, behavior, and/or processes)	Perceptual: identify the objects, the actions and the state (doesn't move horizontally)	Textual	Perceptual: Identify processes (pumped rapidly, pumped) and sensory experiences (warm to touch)	Textual (rapid process)
2. Identify presence of inferred entities based on the state of the phenomenon, and their qualitative properties	Theoretical: naming of inferred entities (Force)	Textual	Theoretical: naming of entities (may be named in the when inferring its properties),	Textual (heat) Symbols (U, W, Q)
	Theoretical: existence of inferred entity	Pictorial: using arrows to represent location and direction of force (can be concurrent when the aspect of physical is identified – link between physical and abstract)	Contextualising: stating behavior of inferred entity (heat does not leave or enter)	Textual (heat does not leave or enter)
	Contextualising: Location and direction of inferred entity on the figure (overlaying the physical)	Gesture (pointing): used to identify the forces as mentioned		
3. Infer the quantitative properties of the inferred entities, justified by scientific laws, rules and principles, knowledge	Contextualizing: quantitative property of the inferred entities	Textual: naming the entity and qualitative property	Theoretical: inferring the quantitative property of inferred quantity	Textual and mathematical symbols (Q = 0)
		Gesture (pointing): for making reference to the force mentioned		
4. Identify a mathematical model that applies to the state of the phenomenon and relate the inferred entities	Theoretical: Newton's second law	Mathematical (F = ma)	Theoretical: First law of thermodynamics; equipartition theorem (Ek = NkT)	Mathematical symbols (U = W + Q; Ek = NkT)

(continued)

Table 12.4 (continued)

	Dynamics		Thermal physics	
General behaviors	Conception	Representations	Conception	Representations
5. Perform mathematical operations to arrive at the quantitative property of the unknown variable in the mathematical equation	(Algorithmic)	–	Algorithmic	Mathematical symbols (U = W), pictorial (arrows – up/down);
6. Conclude the quantitative property of the unknown variable	Contextualizing	Textual	Mathematical	Pictorial symbols; textual
7. Relate the quantitative property of the unknown variable to the observation made.	–	–	Perceptual	Textual

Table 12.5 Representational behaviours observed of producing causal explanations of phenomena of EMI and superposition

	EMI		Superposition	
General behaviors	Conception	Representations	Conception	Representations
1. Simplify phenomenon – key aspects of the phenomenon, naming the phenomenon	Perceptual – presence of objects, their orientation, behavior, properties	Textual – name the objects, orientation, behavior, properties (small)	Perceptual – same pitch	Textual – state properties, naming the phenomenon
		Pictorial – rep of the objects and the perspective of the phenomenon	Theoretical – naming the phenomenon	
2. Identify presence of inferred entities (magnetic fields, waves), and their properties and reify them to produce an analytical structure	Theoretical – magnet and moving electrons produce magnetic fields; magnetic fields' direction and shape	Textual – naming the inferred entities	Theoretical – sound represented by sinusoidal curves, with properties of wavelength and frequency and have coherence	Pictorial – use of waveforms to represent sound and orientate them to represent their nature (coherent sources)
	Contextualising – magnetic fields present in the phenomenon	Pictorial – presence and spatial properties of magnetic fields Gesture – Right hand grip rule to determine magnetic fields direction		
3. State the behavior of one entity on another entity, based on rules and scientific knowledge	Theoretical – vectors so can add them together	Textual – mathematical rule that can be applied to the magnetic fields	Theoretical – amplitude times two	Textual – mathematical rule

(continued)

Table 12.5 (continued)

	EMI		Superposition	
General behaviors	Conception	Representations	Conception	Representations
4. Using the analytical structure, identify the action of one entity on another at different (key) time interval and at different (key) positions/locations	Analytical	Pictorial – arrows in the same direction 'add up' while those in the opposite 'cancel out'; longer arrows used to represent stronger magnetic field, shorter to mean weaker field; helps to think about how one entity acts on another	Analytical	Animation – movement of waves towards each other, time (temporal) Pictorial – height of each wave at two particular points along the wave serves as mediators to think about the amplitude of the wave and hence their magnitude so that the result can be determined (spatial)
5. Conclude with the effect of the action of one entity on another at any time interval and location	Contextualising	Pictorial – use of arrows to show the relative strength	Contextualising	Pictorial/gesturing – position of the new wave at a particular point and the resultant wave and showing how the wave changes at specific point over time.

12.4.3.1 Representational Use in Producing Interpretive Explanations of Phenomena in Dynamics and Thermal Physics

Multiple forms of representations were used in the production of interpretive explanations of dynamics and thermal physics as shown in Table 12.4. These representations clarify and extend the meanings produced in ways that one representation alone might not be able to do so efficiently or effectively.

The construction of the explanations of phenomena in dynamics and thermal physics had mainly been mediated by textual, mathematical and pictorial representations. Textual representations were used almost exclusively for indicating the state of objects or processes as given about the phenomenon (e.g., "the cars are of the same mass", "because it's pumped"), giving a scientific name to an inferred entity when it is identified as being present (e.g., "force", "work done", "energy"), and stating laws (e.g., "according to Newton's laws"). Bearing no resemblance to the real thing or event it signifies, a textual representation is considered an abstraction, and its use in science is based on convention or norm determined by the scientific community. In that sense, its abstractness embodies authoritativeness. By itself, it has limiting capability to extend meaning. Our analysis shows that textual representations are often used with other forms of representations either sequentially or simultaneously.

Text is often used with pictorial representation in the explanation of phenomenon in dynamics. For example, in producing an analytical structure to think about the quantitative properties of the forces acting on the cars and man, verbal text was used to state that "the man push the car". At the same time as the text was spoken, the student drew a horizontal arrow from man to car to show the location and direction that the man acted on the car. In this case, the pictorial representation of the arrow elaborates on the verbal text "push" by giving it spatial properties, hence expanding on the meanings that the text produces.

Text, used in tandem with pictorial representations, can also extend its meaning. We see an instance of this function in turn 34 of Fig. 12.2. The pictorial representation of forces acting on man and cars (arrows) construe nothing other than a spatial description of the forces acting on the objects. The verbal text uttered in turn 34 "the net horizontal force must be zero" defines a means by which the arrows can be related quantitatively. In this case, the arrows pointing in opposite directions were treated in accordance with vector rules so that their net could be zero, which made it possible to conclude that "these two forces is equal" (Fig. 12.2, Turn 34).

At this point we would like to highlight the role of gestures in meaning-making. While the student's left/right gesturing with her finger made simultaneously with the verbal text in turn 34 might not seem meaningful at first glance, it was actually signifying the opposite but parallel forces that needed to be considered for the net horizontal force to be zero. Used together, the text and gesture defined the operations that can be performed with the pictorial representations, hence extending meanings that may otherwise not be possible on their own.

While pictorial representations were not as extensively used in the explanation of thermal physics, its use similarly helped to extend meanings that might be difficult without it. In this case, lines and arrows were put against the individual symbols in the equation of $E_k = NkT$ (refer to Fig. 12.3, Turn 18). These pictorial symbols represent quantitative changes in the internal energy, k and N so that computational thinking about the quantitative changes of these variables can be performed.

In the two interpretive explanations of dynamics and thermal physics (Figs. 12.2 and 12.3), we also see an extensive use of mathematical symbols, especially in producing the explanation of thermal physics. However, its application entailed the shift from the physical phenomenon to the abstract mathematical symbols. Such a shift is dependent on the conventional ways of relating these mathematical symbols to other forms of representations, often determined by scientific or mathematical rules. In the case of the dynamics phenomenon, the identification of the quantitative property of the symbol F entailed the use of pictorial representations to concretise its existence in context so that its presence and properties can be reasoned about. In the case of the thermal physics phenomenon, while there was no similar use of pictorial representations, the institutionalised ways of transforming the physical aspects of the phenomenon (e.g., "it's pumped") to abstract forms (e.g., work done on the gas") was needed to mediate this shift from the physical to the abstract.

12.4.3.2 Representational Use in Producing Causal Explanations of Electromagnetic Induction and Superposition

Like the interpretive explanations of dynamics and thermal physics, the causal explanations also made use of multiple forms of representations in its construction. Similar to the interpretive explanations, text was also used exclusively to name an object (e.g., "the magnet here"), an abstract entity ("there is the electron") and to state rules ("you can actually add them together"). Such exclusive use of text for naming entities and asserting rules reflects the authority that the explainer exerts in meaning-making through textual representations (Table 12.5).

We also observed textual representations being used with other forms of representations to clarify or extend meanings. A clarifying example can be observed in Fig. 12.4 whereby the pictorial representation of the smaller circle within a larger one clarifies the position of "the magnet here". Similarly, in the explanation of superposition, the text "the amplitude from here," used in conjunction with the gesture of pointing, clarified where "here" might be, as well as to signify the magnitude of the amplitude. This gesture can perhaps be seen as a 'shorthand' to identifying the location of the amplitude as well as to bring the interviewer into the explanation. The gesture inscribing the meaning of the magnitude of the amplitude made thinking of the conclusion possible and meaningful.

Pictorial representations and gestures, used together with textual representations, can also extend meanings produced by each form of representation. We found pictorial representations being used more extensively in the causal explanations than in the interpretive explanations. In these cases, abstract entities identified were reified in pictorial forms (e.g., arrows to represent magnetic fields), so as to give it shape and physical properties (direction, strength), as well as location. Such object-like characteristics given to abstract ideas through representations are what Hartshorne (1974) refers to as 'concrete-abstractness'. With the physical properties imbued in them, they could then behave like physical objects that could act on one another (e.g., add up or nullify), so that their properties (e.g., strength of a field) could be changed. In that sense, pictorial representations allow for thinking to be done narratively about the events that could take place. However, the extension of meanings by pictorial representations could not be possible just based on its own affordances. Again, we see multiple representations being used to extend meanings. For example, in the explanation of electromagnetic induction, the rule "you can actually add them together like vectors," inscribed in textual form, defined the ways in which the magnetic fields could act on one another, hence allowing the spatial meanings inscribed by the arrows to be extended to a new field produced with differing strength. This outcome could then be used to think about new processes that could result from it. Likewise, we also find the meanings of the pictorial waveforms to be extended. In this case, besides the textual rule that the amplitudes of the waves were to be added, the gesture of moving the waves towards each other added in the element of time so that new interactions of the waveforms could be reasoned about.

12.5 Discussion

The characteristics of the scientific explanations in physics as exhibited by the case examples are summarised in Table 12.6.

The summary highlights the following key findings:

1. Interpretive and causal explanations were two common forms of response to the request to 'Explain the phenomenon'.

Table 12.6 Summary of characteristics of scientific explanations as shown by the case examples

Dimensions of a scientific explanation	Dynamics	Thermal Physics	Electromagnetic Induction	Superposition
Function	Interpretive	Interpretive	Causal	Causal
Form	Description	Description	Narrative	Narrative
Level of precision	Newton's laws	First law of thermodynamics	(Classical) field theory	Wave theory
Level of complexity	Relevant entities were accounted for and reasons given to support propositions made about the phenomenon were sufficient.			
Level of abstractness	Mathematical symbols and pictorial representations used to represent phenomenon and spatial properties	Mathematical symbols used to represent phenomenon	Pictorial representations used to represent phenomenon and spatial properties	Pictorial representations used to represent phenomenon and spatial properties
	Text used for naming entities and rules, and making conclusions	Text used for naming entities and rules, and making conclusions	Text used for naming entities and rules, and making conclusions	Text used for naming entities and rules, and making conclusions

2. Interpretive explanations of dynamics and thermal physics involved a more descriptive and quantitative style of reasoning, while causal explanations of EMI and superposition involved a more narrative and qualitative style of reasoning.
3. Multiple representations played an important role in producing different types of meanings, and when used together, they clarified, elaborated and extended meanings which other forms of representations might not be able to do effectively or efficiently.

We will discuss each of these key findings in the following sections.

12.5.1 Types of Scientific Explanations in Physics

Interpretive and causal explanations were the two main types of explanations produced among the identified successful explanations. Although science philosophers and even scientists might consider causal explanations as the preferred model of scientific explanation, explanations based on an observed pattern of relationship ('the covering law' as it is also referred to) seem to be commonly found in physics (Braaten and Windschitl 2011). This can be perhaps be explained by the fact that physics (at least the physics curriculum in schools) is dominated by scientific laws (e.g., Newton's laws, Law of conservation of energy, Ohm's law, Laws of reflection/refraction, First law of thermodynamics, Faraday's law). Besides, few theories are introduced in the physics curriculum at the high school level (e.g., kinetic theory, field theory, wave theory). There could, however, be other types of scientific explanations in physics (e.g., predictive) that high school students would encounter. Contextualising and descriptive explanations, we think, are usually found in scientific explanations for lower level physics, while traditional physics classroom activities do not lend themselves to intentional explanations.

12.5.2 Styles of Reasoning in Producing Scientific Explanations in Physics

Findings on how the students went about producing each type of explanation showed that an interpretive explanation tends towards a more descriptive genre compared to the more narrative form of producing a causal explanation. An interpretive explanation, as illustrated in Figs. 12.2 and 12.3, involves the identification of relevant details of the phenomenon (e.g., "he's connected to both suitcase" in Fig. 12.2 and "it is pumped" in Fig. 12.3), and the properties of inferred entities (e.g., "two forces are equal" in Fig. 12.2, and "Q equals zero" in Fig. 12.3), and by connecting these entities with a mathematical model, a conclusion is made. Identifying a relevant scientific law and recreating it mathematically in the context of the given phenomenon, followed by using algorithmic rules to deduce the outcome, thus makes quantitative reasoning possible in an interpretive explanation.

On the other hand, the construction of a causal explanation entails identifying the agent-instrument-target (Lakoff and Johnson 1980) and the actions that take place. In the case of the electromagnetic induction explanation (Fig. 12.3), the magnet and the electron acts as the agents, magnetic fields as the instruments, which will act on each other to effect a change on the electron (the target), causing it to move. In such explanations, the underlying mechanism of how the observation of the slowing down of the magnet takes place need to be detailed.

The dialectical relation between thought and language (Vygotsky 1978) implies that the reasoning process of an interpretive explanation and a causal explanation will be different. The different generic structure of each type of explanation supports this hypothesis. In other words, producing qualitative, narrative form of explanations will require students to ask questions that are fundamentally different from the more quantitative description of interpretive explanations.

12.5.3 Types and Use of Representations in Producing Scientific Explanations in Physics

The use of multiple representations to clarify, elaborate and extend meanings when producing a scientific explanation in physics implies that each form of representation has specific affordances which limit its ability to advance meanings by itself. Table 12.7 summarises the types of representations and their affordances in producing scientific explanations. We discuss each major type in turn.

Textual Representations Textual representation was one of the more commonly used forms of representation in the construction of the interpretive and causal explanations that were produced. Used to produce meanings of identification of objects (e.g., "we have magnet here", "there is the electron") and entities (e.g., "these two magnetic fields"), as well as to provide a statement of laws (e.g., "U = W + Q") and

Table 12.7 Summary of types of representations and their affordances in producing scientific explanation in the case examples

Type of representations	Affordances	Meanings produced
Textual	Abstract and generalised; authoritative	Naming entities/objects, processes; stating laws and theories
Mathematical	Abstract and generalised; can relate entities qualitatively using mathematical rules	Quantitative relationship amongst entities
Pictorial	Form and spatial properties (e.g., location, size, shape)	Spatial meanings (size, location, shape)
Gestural	Time dimension, dynamic	Processes taking place; direct attention

rules (e.g., "magnetic field lines … you can actually add them together like vectors), text is used to represent the abstract nature of inferred entities such as magnetic fields and work (W), heat (Q), which often bear no resemblance to the real thing or event they signify; they are man-made and institutionalised. In that sense, its abstractness embodies authoritativeness. Its abstractness meant that its meaning needs to be reconstructed in the context to which it is to be applied. By itself, it has limiting capability for extending meaning; it needs to be used with other forms of representations to realise the potential meanings it embodies. When used with other representations, they play a crucial role in extending meanings.

Pictorial Representations Pictorial representations are often used to reify inferred entities (e.g., force, magnetic fields, waves), as we see in the explanations produced. Pictorial representations such as the sinusoidal wave pattern (refer to excerpt in Fig. 12.5) and arrows (refer to excerpt in Fig. 12.2) give physical (in particular spatial) form and quantitative properties to an otherwise abstract concept of sound and force respectively. Pictorial representations seem crucial for aiding reasoning about the entities, whether qualitatively or quantitatively. In causal explanations such as that of EMI, by drawing out and arranging the magnetic fields of an electron and magnet spatially, an analytical structure (Kress and van Leuwen 2006) made up of lines behaving as "objects" is produced that allowed thinking about what and how the magnetic fields can act on one another. In interpretive explanations, pictorial representations can also support quantitative reasoning. As can be seen in the explanation of thermal physics, the arrows/line placed against the symbols (W, U and Q) representing a physical quantity, did not give form to any entity; instead they were substitutes of numbers so that the students could think about how quantitative changes in one variable may affect the changes in quantitative property of another. In this sense, pictorial representations are useful in producing spatial meanings and indicate quantitative changes in entities.

Gestures Gestures were less commonly found in these four explanations we analysed, and perhaps least researched about in science education. While often thought to be ancillary to other more dominant forms of representations, Roth (2006) showed that gestures can play an important role in science teaching and learning. A close examination of the gestures used in the explanations in this study showed how gestures contributed towards the production of a scientific explanation in these examples.

Well-known for their deictic function, gestures are efficient tools to make specific references to indexical text used in verbal communication (e.g, "here", "this"). But gestures also have the capability of adding in the element of time into explanations, which we see in the explanation of superposition (Figure 12.5, Turn 21, first picture). By animating the movement of the two waves moving towards each other, a fourth dimension of time was added into the explanation hence allowing new processes over a period of time to be thought about.

Gestures are also effective tools for producing spatial meanings. We see that in the explanation of dynamics (Fig. 12.2 Turn 34, first picture) whereby the sideways gestures with the student's hand was an indication of the direction of the forces to be considered in order to achieve a "net horizontal force is zero" (Turn 34, picture). With the gesture preceding the conclusion about the two forces, we infer that it functioned as a sort of metaphorical representation of the horizontal forces acting, which then allowed the student to identify and conclude which forces were equal to each other.

Use of Mathematical Symbols Mathematical symbols are often used to represent inferred entities (e.g., "F" represents force, "U" represents internal energy). Unlike pictorial representations, these mathematical symbols embody quantitative properties only. Following the rules of mathematics, these mathematical symbols can be arranged into a mathematical equation in order to define the quantitative relationship among the entities. In that sense, a mathematical equation (e.g., "F = ma", "U = Q + W") is an analytical structure that allows mathematical computation to take place, once the quantitative properties of the variables in the equation are known. In other words, mathematical symbols and equations are necessary representations for quantitative reasoning. However, like textual representations, they are very abstract in nature. Hence, its use necessitates a reconstruction of the mathematical model in the physical system by producing a model of the physical system with these mathematical symbols so that they can be processed mathematically in order to interpret the physical system (Redish and Kuo 2015).

The unique affordances of each form of representations in producing scientific explanations imply that students need to develop "representational capabilities" (Gilbert et al. 2000) to produce scientific explanations. This include the ability to

1. Differentiate the affordances, and limitations, of different forms of representations, formal or informal;
2. Select and use the affordances of each form of representations to clarify, elaborate and extend meanings when producing different types of scientific explanations.
3. Understand why one form of representation may be more effective than another to produce some types of meanings

12.6 Conclusion

This study started with the aim of understanding how students used representations to produce scientific explanations. The types of representations used (modes as well as formal or informal), affordances of different types of representations for meaning-making, and the roles of a system of multiple representations in clarifying, elaborating and extending meanings demonstrate the epistemological, cognitive and cultural dimensions of multiple representations in realising the function, form and level of a scientific explanation.

The different systems of representations used in producing interpretive explanations and causal explanations highlight the epistemological function of representations in different types of explanations. The dominance of mathematical representations used to produce an interpretive explanation reflects the view that science illuminates regularities of the natural world that can be expressed mathematically to show its behavioural patterns. From this perspective, explanation for an observed event would entail using these natural laws to show that the event is a logical and expected outcome based on well-established patterns. On the other hand, causal explanation seeks to understand the mechanism underlying events we see/experience around us. Such explanations assume the action or behavior of an agent on a target that brings about an effect. These explanations are often based on theories that assume the presence of abstract entities (e.g., magnetic field lines). The use of pictorial representations thus gives physical form to abstract entities so that these representations can be given object-like properties that can interact with each other (e.g., push each other, add or cancel one another). In that sense, we consider a system of multiple representations as having an epistemological dimension, which realises the different functions of scientific explanation.

The construction of a scientific explanation has been shown to involve a complex orchestration of multiple modes of representations to clarify, elaborate and extend meanings, in which its organisation reflects the form of the scientific explanation produced. The realisation of the form of the scientific explanation by a system of representations suggests the cognitive function of multiple representations.

The production of a scientific explanation requires a student to recontextualise the genre of school science encountered in class: the different explanatory models, the formal (scientific) representations introduced in class and the scientific discourse. This entails the student having to make complex decisions about selecting the formal representations (vs informal representations) so that the representational elements put together can contribute towards the realisation of 'being scientific'.

In short, a system of multiple representations used for producing a scientific explanation embodies epistemological, cognitive and cultural meanings that realises the three dimensions that characterises a scientific explanation – function, form and level. An implication of this intimate relationship between multiple representations and the construction of scientific explanation in physics to teaching and learning of physics is that developing students' representational-capabilities for producing scientific explanations need to go beyond conceptual understanding. Focusing on the representational resources and their potential to produce epistemological, cognitive and cultural meanings should also be considered.

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Chapter 13
Cross Referencing to Co-construct Knowledge About Global Heat Transfer in an Online Learning Environment: Learning with Multiple Visualizations

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13.1 Introduction

The purpose of this study was to design and develop an online, virtual interactive textbook (VIT) to facilitate teaching and learning about the phenomena of global heat transfer. Our Global Heat Transport System VIT features a number of multiple representations presented as visualizations (videos, animations, simulations), which were designed to aid student understanding of how convection, Hadley cells, and the rotation of the earth on its axis result in the various weather patterns experienced around the planet. Such understanding is vital, especially given changes to weather patterns that are predicted due to global warming (Parry et al. 2007). Through understanding the process of global heat transfer, students may be better able to reason about the potential effects of hotter temperatures at the equator on global weather patterns. Specifically, the goal was to look at ways to highlight some basic physical principles that underpin the behavior of the climate system. The module presented focusses on twin processes of (i) planetary scale pole equator temperature differences and (ii) Earth rotation. It explores the consequences of temperature gradients in air in the classroom and then uses interactive tools to connect the classroom illustration to the analogous planetary scale dynamics.

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13.2 Representational Competence

A primary goal of our work is to develop digital environments that facilitate student understanding of large scale, Earth science phenomena, such as global heat transfer. Foundational to such understanding is the ability to meaningfully interpret different representations of the phenomena. This type of understanding is referred to as representational competence (Kozma & Russell 2005). For example, learners must be able to understand how a specific representation encodes information in order to be able to make sense of that information (Ainsworth 2006), and at higher levels, the goal is to assist students in reading across various representations to approach a deeper understanding of scientific phenomenon (Kozma 2003).

New technologies have afforded us the ability to develop new scientific representations of phenomena. In our work, we are seeking to develop meaningful, interactive representations that facilitate student understanding in the area of earth science through the use of real time data made available through cloud computing. In this project, we have developed a virtual experiment that features an abstract visualization of the process of convection with two manipulable parameters (temperature and rotations). In order to support student understanding of this representation at the level of encoded information (Ainsworth 2006), we designed a VIT that features sequenced, multiple visual representations of the process of convection and of global weather patterns (Ainsworth 1999).

Scalise et al. (2011) in a comprehensive literature review of student learning in science simulations point out that while multiple representations appear to aid student learning, more research is needed in understanding how "…to use representations effectively to complement, constrain and construct understanding" (p. 1068). Furthermore, they add that visualizations and animations of either very small or very large phenomena should be helpful in aiding students' comprehension of such phenomena. Our work focuses on a very large phenomenon: global heat transfer. We sought, through the design and development of a primarily visual and visually interactive online environment, to examine the effects of such instructional design on student learning of the phenomenon.

An important pedagogical aspect of the implementation of our Global Heat Transfer VIT unit was collaboration; students worked together in collaborative dyads to view, interact with and make sense of the various representations. We chose to utilize this pedagogical approach because students who engage in collaborative learning in ill-structured domains achieve higher levels of understanding (in comparison to individuals) if they engage in high levels of discourse (Cohen 1994; Mercer 1996) and if they work in a coordinated fashion with one another (Barron 2000). In having students collaborate we hoped to not only improve potential learning outcomes, but also to provide a mechanism that would allow us to study student reasoning with the representations. Our work responds to Scalise et al.'s (2011) recommendation that more research be done on understanding "how" students interact with and make sense of representations. Therefore, our research questions were:

(1) Did students show evidence of a gain in content understanding related to global heat transfer after studying in our VIT?; (2) How did students utilize the representations to reason and/or think, collaboratively, about the phenomenon?; and (3) How did students interpret the various representations towards the goal of meaning making?

13.3 Design of the VIT

The research team worked closely with four middle-school science teachers to design the VIT. Prior research has shown that involving teachers in the design and development of curriculum materials, such as our VIT, results in positive outcomes for students in terms of conceptual understanding (Pan et al. 2012). Moreover, involving teachers in the design supports important pedagogical shifts for teachers, including a more active learning role for students (Li 2012) and using strategies that are more likely to result in student learning "such as prompting students for explanations and interpretations, not just recall of facts" (Shear & Penuel 2010, p. 50).

We met with the teachers on a bi-weekly basis for 4 months. During this time, the group focused on both the scope of the unit, as well as the nature and sequence of the visualizations to be used in the VIT. We elected to divide this unit of the VIT into two chapters. The first chapter, "Heat Transfer and the Earth's Atmosphere," introduced students to the basic concept of convection. The second chapter, "Heat Transport and the Global Weather System," introduced the role of the rotation of the earth and the process of convection in creating global weather patterns. Weather is a topic that is covered in sixth grade in the state of Massachusetts. So, students had some prior knowledge of the topic. Each of the visualizations was accompanied by a prompt that aimed to scaffold dyadic, collaborative student interactions while viewing the representation. These prompts are discussed further below.

13.3.1 Visual Representations

We based the design of our visualizations on the work of two researchers: Gilbert (2008) and Ainsworth (1999), we discuss each in turn. Gilbert suggests a dimensional system that scaffolds student understanding from more concrete, macro-level, 3D representations, defined as "perceptions of the world-as-experienced" (p. 7) to 2D, sub-micro-level representations, defined as "photographs, virtual representations, diagrams, graphs, data arrays" (p. 7) to the more abstract 1D representations, defined as "symbols and equations" (p. 7). This reduction in dimensionality is introduced once students are able to mentally represent the 3D and 2D visualizations on their own. As students learn to progressively model the phenomenon, the need for robust visualizations is decreased and students can meaningfully employ the more abstract one-dimensional representations. In our VIT, we sought to present students with 3D and 2D visualizations towards the goal of meaningfully interpreting the 1D information requested of them in the final virtual experiment presented in the unit. We describe the dimensionality of each visual representation in the next section.

Meanwhile, Ainsworth (1999) has defined a functional taxonomy of three primary uses of multiple external representations for learning in a domain: to complement information that is provided, to constrain (mis)interpretations of the representation, and to construct a deeper understanding of the phenomenon represented. In terms of Ainsworth's taxonomy, chapter one of our VIT was designed with the goal of constraining (mis)interpretations. In other words, we hoped to introduce familiar representations in order to support student understanding of less familiar, more abstract representations. In chapter one, each representation depicts the same thing: the process of convection. Specific to the reasoning of using familiar representations we sought to connect the visualizations in our VIT to recent significant, anomalous weather events in the area, with which the students would be familiar. In our case we related classroom convection illustrations to convection found in severe storms that had recently impacted the local school systems involved in the project. Theoretically, this also enabled us to build on students' prior knowledge (Piaget & Inhelder 1969/2000).

The New England city where the research took place had recently experienced both a hurricane and a tornado. In the summer and fall months prior to the late spring implementation of our project, both weather events had occurred in the area with newsworthy ill effects. The tornado was particularly devastating as it destroyed several buildings and residences in the downtown area of the largest area city (where two of the participating classes were located).

Therefore, to connect the content of our unit to students' prior knowledge, the first visualization the students encountered in chapter one was a time-lapsed video of a real-life thundercloud forming. This first visualization is a 3D video that depicts a macro-level phenomenon, one that students would immediately recognize from their own experience. Next, based on the teachers input, we presented two visualizations, which depicted classroom-based, laboratory experiments. The first of these visualizations uses photographic images of cold and hot water mixing in a bifurcated beaker to demonstrate the process of convection as it unfolds when hot water and cold water mix. In this visualization, the hot water contained red dye. Students were able to view the upward trajectory of the reddened hot water in the bifurcated beaker. This visualization may be thought of as a 2D depiction. While these images of the water mixing were not at the sub-micro level, they were laboratory-based photographs that simulated a real life phenomenon. The next visualization was a video that showed the process of convection using a spiral shaped piece of paper tied beneath a pie plate full of ice, both of which were then suspended over a lighted candle. As the lighted candle was moved from beneath the tray and back again, the spiral shaped paper moved up and down (down as the cool air moves down – up as the hot air moves up). This visualization spans the 3D and 2D category. The visualization presents a real world, macro phenomenon on a small scale.

The first chapter of the VIT unit ends with the presentation of two abstract still images: a depiction of Hadley Cells (Fig. 13.1), and an image of a sphere depicting global convection (Fig. 13.2). These still images fall squarely in the 2D category as they are diagrams that depict a 3D phenomenon. In this way, the visualizations in chapter one of the VIT move from concrete, macro depictions of the phenomenon of convection that use familiar elements that are easy to interpret and understand

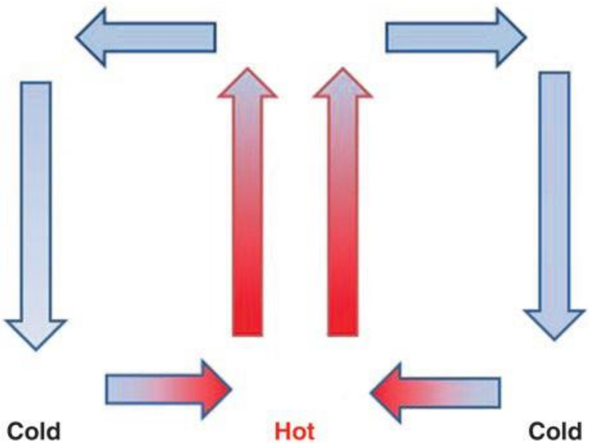

Fig. 13.1 Hadley cells

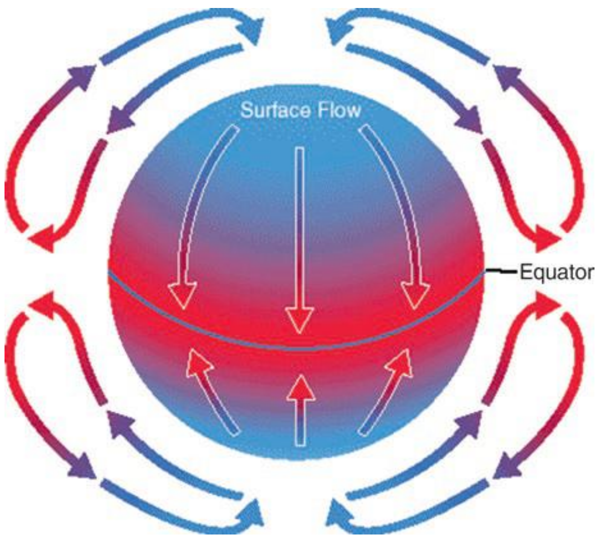

Fig. 13.2 Global convection sphere

(thunderclouds forming) to smaller level depictions (hot (red dye) and cold water mixing, hot air (lighted candle) and cold air (pie plate of ice) mixing), to diagrammatic, more abstract representations of the process of convection (Hadley Cells).

The second chapter of the VIT was designed based on Ainsworth's (1999) notion of complementary information. In this approach, each representation offers some new information to the student and also provides some shared information. These representations allow students to reason about different dimensions of the problem by featuring specific elements of the phenomena.

Chapter two of the VIT unit contains six visualizations, all of which are presented at the 2D level. These visualizations present photographic, simulative and imagistic representations of the process of convection on a global scale and the rotation of the Earth. The first of these visualizations is a still image, computer graphic of the Earth. This image was presented to students on a sheet of paper and they were asked to draw what the weather would look like if convection were the only cause of the Earth's weather patterns. This was the only visualization for which students were asked to contribute from their creativity. The next five visualizations were as follows: (1) a TV weather report (focusing on the *directionality* of storms); (2) a simulation of global weather patterns produced and disseminated by the National Oceanic and Atmospheric Administration (NOAA) (focusing on the *shape and directionality* of major storms); (3) a video of a university-based, classroom experiment that simulates global weather patterns using a device that re-creates the relationship of hot air at the equator, the rotation of the Earth and the movement of air around the globe – this is done through the use of red and green dye in a rotating tank (creating swirling eddies that *resemble* storm cloud masses); (4) an animation of temperature data over the United States over the course of a year (emphasizing the *temporal* aspect of weather); and (5) the introduction of the virtual experiment environment, with an explanatory video. The virtual experiment environment itself included both 2D and 1D elements (Fig. 13.3). The 2D elements include the virtual representation of the Earth at its poles. The 1D elements included the interactive rotation and temperature fields where students could select different parameters to explore the development of various weather patterns.

The goals of the visualizations in chapter two were threefold: first, we sought to introduce the role of the rotation of the Earth into students' understanding of the production of global weather patterns; second, we sought to bring together the ideas of convection and the rotation of the Earth into a coherent system of explanation of global weather patterns; and third, we sought to prepare the students to accurately interpret and meaningfully engage with the virtual experiment representation. As regards the first two goals, our VIT focused on introducing students to the phenomenological effects of convection and rotation. Students saw that convection in fluid was driven by warming or cooling and that fluid flow would change with rotation rates. Classroom time constraints did not allow for deriving analytical models and quantitative relations, although in principle that would be possible.

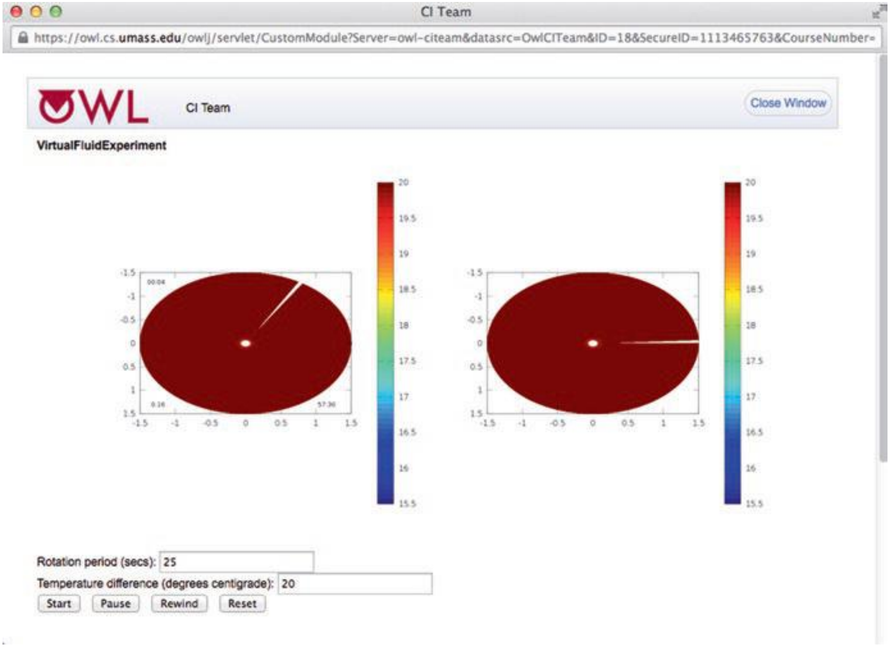

Fig. 13.3 Virtual convection experiment

13.3.2 *Scaffolding Prompts*

As mentioned above, each of the visualizations in chapters one and two were accompanied by a prompt. These prompts generally called for student conversation and then directed students to record observations in a researchers' journal. The exact nature of each prompt is described below, in the methods section. For this particular instantiation of our VIT, the researcher's journal was provided separately from the website in the form of an electronic document. These documents resided locally on the respective hard drives of the computers in each school. The prompts existed both on the website, below the visualization, and on the electronic researcher's journal. In addition to the visualizations and the prompts, the VIT included a glossary of terms.

The general student activities in this project included iterative viewing of the visualizations and collaborative discussion (scaffolded by the prompts) followed by a recording of student observations and reflections in the researcher's journal. The teachers also engaged the students in whole class discussion of the activities. These discussions mostly occurred in a summative fashion at the end of class, though, the teachers engaged with the students throughout the class through answering student-initiated questions.

13.4 Methods, Data Sources and Data Analysis

Participants in the study were recruited from public middle schools in two urban areas in Western Massachusetts. These schools educate students who are underserved in the USA public school system, and who are underrepresented in the Science, Technology, Engineering and Mathematics (STEM) disciplines at University and in STEM careers. An educational policy goal of the federal government in the USA is to increase participation of underrepresented students in the STEM disciplines. One way to increase participation is to improve underrepresented students' exposure to STEM learning experiences. Hence, we recruited middle school science teachers from these urban centers to work with us in order to work with their students. Teachers who elected to take part in the research study did so voluntarily, based on their interest in the project. Therefore, our participants included the four teachers who helped design the VIT and their eighth grade science students. There were a total of 61 students across the four classrooms, due to attendance issues, 43 students participated in this study. These students, who came from three schools in two urban settings in Western Massachusetts, are representative of those students who are underrepresented in STEM.

13.4.1 Classroom Implementation

The Global Heat Transport System VIT unit required a total of 160 min of class time. Two of the participating schools had 90-min class periods and were, therefore, able to implement the unit on two consecutive days. Two of the schools had 45-min class periods and implemented the unit on four consecutive days. In each school, the VIT curriculum unit was enacted by the teacher near the end of the school year. One researcher and one research assistant attended each of the class sessions in order to collect research data. Since the teacher/researcher design group had met many times prior to the enactment, decisions had been made about how the teacher would introduce the research project, the topic of the VIT, and the technology to be used in the classroom. Each teacher used a whiteboard that served as a projector for the VIT unit to lead class discussions at specific times during the implementation. Class discussions occurred after the students had time to interact with the technology and respond to question prompts in their online researcher journals (see Appendix A).

13.4.2 Research Design

We employed a convergent parallel mixed methods design to address our research questions (Creswell 2014). The convergent parallel mixed methods approach uses both quantitative and qualitative data to converge on answers to the same research questions (Creswell). Our research design incorporates gathering data through a repeated measures pretest-posttest, audio and videotaped observations, and the collection of the online researcher journals. All of the data collected relates to student learning of the process of convection. The quantitative pretest-posttest focuses on gains in conceptual understanding, while the qualitative analysis focuses on the process of learning students engaged in, and in particular, the process of engaging with the visualizations. The pretest and posttest were administered to answer Research Question 1: Did students show evidence of a gain in content understanding related to global heat transfer after studying in our VIT? Forty-three students completed both the pretest and the posttest. Each test consisted of eight questions, seven of which related to convection and one to the rotation of the Earth. The questions were the same on each test. The tests were given at the beginning and the end of the unit. The Earth scientist on the research team developed the pretest and the posttest. Cronbach's alpha was utilized to establish the reliability of the test. T-tests were performed to analyze any differences between the pretest and the posttest scores.

In order to address Research Question 2: How did students utilize the representations to reason and/or think, collaboratively, about the phenomenon?, four collaborative dyads (one from each class) were video and audio taped as they interacted with the VIT and with each other. These dyads were chosen in consultation with the participating teachers. Since our goal was to understand how students thought about the visualizations, it was important to select dyads that would, reliably, engage in discussion with one another. Therefore, the respective teachers selected students they believed would be best able to collaborate through discussion.

All of the whole class discussions were also recorded. We transcribed the audio portions of the collaborative dyadic interactions and of whole class discussions captured on the videos. We then used a computational method based on theoretically derived keyword searches to identify conceptually rich sections of the discussions (Sullivan 2014). For the purposes of this study, we defined conceptually rich sections of the data as one's in which students used the vocabulary of the unit (e.g., "equator," "heat," "cycle,"). In so doing, we developed the understanding that, in fact, students and teachers were referring to the representations as a means of *scaffolding* understanding. Based on this understanding, we developed a classification scheme that allowed us to identify the type of scaffold the teachers and the students were using in interacting with the representations towards the goal of knowledge co-construction. The three types of scaffolds were conceptual, metacognitive, and representational. For the purposes of this study, conceptual scaffolds are defined as verbal interactions about the representations that focus on conceptual aspects of the phenomenon (e.g., hot air rises, the earth is hotter at the equator, the Hadley Cell represents a cycle, storms move from west to east in the northern hemisphere, etc.). Metacognitive scaffolds are defined as prompts that serve to focus students on thinking about how they are viewing, working with and/or thinking about the visualizations. Finally, representational scaffolds are defined as those verbal interactions that explain or point to specific elements of a specific representation. The research team collaboratively interpreted utterances as specific types of scaffolds. We took this approach because these classifications are descriptive. They serve to illuminate the cognitive interactions of the participants as they interacted with the VIT. While we have enumerated the number of specific types of utterances we identified, we have not used the enumeration to perform predictive analytical tests on participants' behavior.

In order to address Research Question 3: How did students interpret the various representations towards the goal of meaning making?, we analyzed the student research journal responses. Only two students completed all of the questions asked in the journal. However, 30 of the students answered at least eight of the 12 prompts. We chose to include these 30 journals in our analysis. The electronic journal consisted of 12 free-response prompts, which required students to record, describe, or hypothesize about each of the visualizations they studied in the 2-day lesson.

The first four prompts required students to describe what they witnessed in four video visualizations regarding convection, three visualizations from chapter one and one from chapter two of the VIT. The video topics included thunderstorm formation, the movement of hot and cold water, the rotation of a spiral shaped piece of paper due to heat, and a national weather forecast. Prompts five through seven asked students to provide three discrete observations about the movement of global weather based on the NOAA simulation video from chapter two of the VIT. Prompt eight asked students to create a hypothesis about weather patterns if convection currents were the only cause of weather. Question prompts nine and ten asked students to make observations about how meteorologists predict weather based on the provided weather animations from chapter two of the VIT. Lastly, question prompts 11 and 12 required students to make two observations related to representations of global weather patterns created as a result of two virtual experiment trials.

To analyze the replies to these prompts, the research team employed a modified version of Kozma and Russell's (2005) summary of representational competence levels. Kozma and Russell's original levels were developed for understanding student *created* representations pertaining to chemistry. The modified competency table was developed by the research team in order to specifically address the students' *interpretation* of representations as they applied to the concepts of convection and weather. Table 13.1 presents our classification scheme for levels of interpretation of representation with examples drawn from our data set.

Two graduate student research assistants were trained on the coding system. The coded journals [n = 30] consisted of 300 completed items and 60 missing items ($\alpha = .67$). Inter-rater reliability was calculated using Krippendorff's (2004) Alpha Reliability Estimate for nominal data, any number of observers, missing data. Disagreement in the coded responses was resolved for the full sample by discussing individual discrepancies. The two coders discussed differences and assigned an agreed upon rating to the student response. The results are presented in a side by side fashion (quantitative first, qualitative second), as is typical of the convergent parallel mixed methods approach (Creswell 2014).

Table 13.1 Levels of interpretation of representations

Levels of interpretation of representation	Description for codes	Examples from our data
Level 1 – Interpretation of representation as physical description.	When asked to interpret a representation of a physical phenomenon, the student(s) focuses on the physical features of the phenomenon only.	"The clouds are swirling."
Level 2 – Interpretation of representation in terms of observable cause.	When asked to interpret a representation of a physical phenomenon, the student(s) focuses on the physical features of the phenomenon and adds some mention of observable causes (e.g., wind, the candle, the ice).	"I think the clouds are moving in the way the wind is moving."
Level 3 –interpretations of representations in terms of unobservable cause.	When asked to interpret a representation of a physical phenomenon, the student(s) focuses on the physical features of the phenomenon and some mention of unobservable causes (heat, cold).	"I think in the video the clouds are getting bigger. Also the clouds seem to be moving to the left. The clouds are rising up. I think the heat are rising [sic] the clouds. Heat rises while cold sinks."
Level 4 – Interpretations of representations in terms of systematic elaborated linkages among unobservable causes (scientific explanations).	When asked to interpret a representation of a physical phenomenon, the student(s) focuses on the physical features of the phenomenon and provides an elaboration of systematic linkages in unobservable causes (condensing, water to gas).	"The video is showing how the clouds move over a period of time. They are probably condensing so that it would rain. The hot air is going into the cold air that's why the clouds are moving up. The water from the ground turns into a gas and mixes in with the clouds. The video shows that the wind is pushing towards the clouds. All the air is rushing to the clouds away from whoever is watching the clouds in the video."
Level 5 – Cross referencing of representations.	Translating or referring to a different representation in explaining the current one.	"I think they (two visualizations) do not match because the earth is constantly spinning."

13.5 Results

13.5.1 Repeated Measures

As regards Research Question 1: Did students show evidence of a gain in content understanding related to global heat transfer after studying in our VIT? – we performed a paired samples t-test to compare students' scores on the pretest and the posttest. The test revealed a statistically significant difference ($t(42) = -7.10$, p = .000) in mean student responses related to convection and rotation; the mean for the pretest was (M = 3.60, SD = 1.61) and for the posttest was (M = 5.72, SD = 1.71). Students, on average, answered two more questions correctly on the posttest than they did on the pretest. While these results are encouraging, we found that the test itself did not have a high degree of reliability. Cronbach's alpha was calculated on the posttest at .49 for all 8 items. When we removed question #2 (related to convection as a process that also occurs when cold and hot water meet), alpha improved to .57, which is still low. Therefore, these findings should be interpreted cautiously.

13.5.2 Collaborative Discussions

As regards Research Question 2: How did students utilize the representations to reason and/or think about the phenomenon?, our initial analysis of the conceptually rich discourse allowed us to identify the fact that students were verbally cross-referencing the various visualizations in a reasoning process of knowledge co-construction. Table 13.2 presents a discussion between Abby (A) and Sara (S) (pseudonyms) which depicts the cross-referencing of visualizations and how doing so allowed the girls to co-construct knowledge of the phenomenon of convection. This discussion takes place towards the end of the students' study of section one on day one when they are viewing the fourth visualization, the Hadley cells and the global sphere representation of convection (Figs. 13.1 and 13.2). In Table 13.2, the direct reference to the content of other visualizations is denoted in bold.

As can be seen in this example, the students are still working towards developing a stable understanding of convection. In this instance, cross-referencing the visualizations is helping them both reason about the phenomenon, and also learn to interpret different dimensional representations of convection (real world, photographic, diagrammatic). In essence cross-referencing the visualizations acted as a scaffold to student understanding.

We found that a majority of student and teacher verbal interactions at the dyadic level were comments that could be viewed as scaffolding comments. As noted in the methods section, we identified three types of scaffolds: conceptual scaffolds (as in Table 13.2), representational scaffolds and metacognitive scaffolds. Furthermore, we found that while students and teachers used each type of scaffold in their verbal interactions, students appear to engage in more conceptual scaffolding with one another, and teachers appear to engage in more metacognitive scaffolding with the students. Table 13.3 shows the distribution of the types of scaffolds across teachers and students.

Within the three scaffolding categories, we noticed nuances in the delivery of the scaffold for both students and teachers. As regards the area of conceptual scaffolding, we found that students either: (1) explained the concepts to one another through *cross-referencing* the visualizations (as shown in Table 13.2); or (2) they *explained* the representations to one another in terms of the concepts; or (3) they made *analogies* with the representations to aid conceptual understanding. Examples of these two latter types of student uttered conceptual scaffolds are provided in Table 13.4.

Table 13.2 Cross-referencing visualizations

Utterance	Reference to other visualization in Chap. 1
A: Right here the heat it's supposed to go up, and when turns cool goes back down. And repeat the process (points to the Hadley Cells).	Fourth visualization
S: So it's like a cycle.	
A: Yeah, and here the same thing, except that it goes to the middle. The heat its forced to go to the equator (pointing to the globe convection sphere).	Fourth visualization
S: That thing, it's more than... [inaudible]. Oops, Ok.	
A: Like that (moves her computer closer to show Sara).	
S: I just want to know, how that can be cool, right here, and right here it's just hot (points out with her fingers to the arrows of the Hadley cells).	Fourth visualization
A: Cuz it starts to get hot right here and ... [inaudible] (points to the arrows that go up).	Fourth visualization
S: Oh cuz I…like the floor. So you like from up here, its cooler up here than down there, and then when you go down the floor its hotter…**Cuz like the main thunderstorm.** Ok, ok I get you. I'm sorry. This one... (Scrolling down her computer screen to the global convection sphere).	First visualization
S: This right here are [sic] just doing umm, are doing cycles like this (pointing to the arrows outside the globe), and this are [sic] just pressing towards in the middle, the center (pointing to the arrows inside the globe)	Fourth visualization
S: So I see up here appears cool like moving the heat from here so I can go here. Ok It's going to be ___ right? (Changes the page to her Journal and scroll it down to the end) Holy camoly! National weather, right?	
Teacher: Think about all the things that you just saw (Background)	
S: **Oh you know like that, like that candle.** She had the heat right there	Third visualization
A: Yeah	
S: **And the ice tray up there.** Looks kinda like that's (pointing to the Hadley cells)	Third and fourth visualization
A: And the, it's suppose to, to go down. In this case, it can go sideways.	Fourth visualization
S: You can go all places but up. Oh yeah like, oh sorry, I just remember that heat always goes up and cool air always goes down. Ok.	
A: **Not just air it could be a liquid too**	Second visualization
S: Ok a liquid, but we are talking about air right now.	

The teachers also demonstrated a nuanced approach to scaffolding within the three overarching categories. For example, in terms of conceptual scaffolding the teachers also either *explained* the representation to scaffold conceptual understanding or *cross-referenced* the visualizations to scaffold understanding.

As far as the metacognitive scaffolds are concerned, the teachers used three approaches: c*ross-referencing* as a learning technique; urging students to contextualize their current learning in *prior learning*; and guiding student activity by urging

Table 13.3 Scaffolding by type and role

	Student	Teacher
Conceptual	13	4
Metacognitive	1	9
Representational	0	28

Table 13.4 Two types of student conceptual scaffolds

Explanatory conceptual scaffold – Example #1	K: ((Uses his pencil to point to the image of the Global Convection Sphere (Fig. 13.2)).
	So, yeah, Arturo, since the equator it's the hottest so the sun, its right here, so, when the cold air goes down here, the cold air turns hot. So, when it comes back up here, this is cold, so, the sun its not there, so, like comes right here. It's really cold. So, each time it gets close to the equator it gets hot, when it gets away from it, it gets cold.
Explanatory conceptual scaffold – Example #2	S: Oh, there's ice right here ((points at the pie plate)). So ice, its cool. Oh, I didn't know it was there. Okay, apparently the cool air it's like right here ((points at the pie plate)) and this is the warm ((points at the candle)). You know what I'm saying?
Analogous conceptual scaffold – Example #1	B: That's so cool! Sorry. Hey, they're moving like currents, kind of, 'cause you see how this one's moving this way and these are moving up?
Analogous conceptual scaffold – Example #2	K: Wow, its like a storm, but it happened… its like tornados and hurricanes coming.
	Y: It looks like this is showing, like volcanoes or something.

Table 13.5 Three types of teachers' metacognitive scaffolds

Metacognitive Scaffold – Cross-reference– Example #1	T: So, when you're thinking about that and you're looking at these pictures, reflect back on 1.1, 1.2, and 1.3. Now try to make sense of these pictures, use intelligent words and have a conversation with the person next to you about what's happening here.
Metacognitive scaffold – Contextualize in prior learning – Example #1	T: Alright, I think, I think I'd like to say one thing, so you kinda make sense of what you're looking at. Remember sixth grade science? I had you in sixth grade, alright? Sixth grade science, the Earth, the sun, flash lights on balls.
Metacognitive scaffold – science literacy prompts – Example #1	T: Click on, all you do is click play. Are you there? Alright. Watch. Just observe it. What's occurring? You see a large beaker, smaller beaker submerged inside a larger beaker. You can see the smaller beaker has a covering, okay? And it appears that they did something to the covering. You might have to watch it again closely. I know I had to watch this a couple of times.

them to "*observe*" *and/or* "*notice*" what was happening in the visualizations. We came to think of this latter example as prompts towards the development of science literacy, as observation is at the root of much scientific research practice. Table 13.5 presents examples of these types of metacognitive scaffolds provided by the teacher.

Finally, as regards the representational scaffolds the teachers either: described the representations ahead of time as a *procedural* scaffold; or pointed out *specific elements* of specific representations to aid in the encoding of information; or asked students to

Table 13.6 Three types of teachers' representational scaffolds

Representational Scaffold – Procedural – Example #1	T: Based on what you know so far we're going to look at this video. This video has, as it says in the directions, it has a pie plate with, filled with ice and it has a candle providing the heat, and a piece of paper that's corkscrewed down. So, watch this video, and use the words that you have learned and understood, and explain in your researcher's journal what is happening in the video, based on what you know. But, remember, this is happening not in water, but in air.
Representational scaffold pointed out specific elements – Example #1	T: Alright so, looking at the red arrows, blue arrows and purple arrows, so, now intelligents, let's have a conversation, what's going on there?
Representational scaffold they asked students to explain – Example #1	T: Yeah, it was all dark, okay? And then it got red. So, what did the red represent? What colors did it change to?

Table 13.7 Levels of interpretation of the representations – responses by prompt

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	Total (1–12)	Total (% Resp)
L1	15	17	5	22	28	28	22	6	26	18	15	13	***215***	***71.67%***
L2	2	2	1	1	1	0	0	1	0	2	0	1	***11***	***3.67%***
L3	12	9	19	3	1	1	2	13	0	2	1	1	***64***	***21.33%***
L4	1	2	2	0	0	0	0	2	0	0	0	0	***7***	***2.33%***
L5	0	0	2	1	0	0	0	0	0	0	0	0	***3***	***1.00%***
TOTAL answered	***30***	***30***	***29***	***27***	***30***	***29***	***24***	***22***	***26***	***22***	***16***	***15***	***300***	***100%***
Missing responses	***0***	***0***	***1***	***3***	***0***	***1***	***6***	***8***	***4***	***8***	***14***	***15***	***60***	–

explain the representation to them as a means of scaffolding their understanding. Table 13.6 provides an example of these types of representational scaffolds.

13.5.3 Student Researcher Journals

Finally, to answer Research Question 3: How did students interpret the various representations towards the goal of meaning making?, we analyzed the written responses provided on the student research journals based on the prompts. As can be seen from Table 13.7, many of the students provided a level one interpretation of the representation for many of the question prompts. However, several students also provided level three interpretations on various questions, and a few students were able to provide level four and level five reflections on a few of the questions. The researcher journal was provided to students as a means of scaffolding their interactions with the visualizations, they were not graded and were not reviewed by the participating teachers. In this way, it is possible that students did not spend as much time and attentiveness on completing the journals as they might otherwise have done. Moreover, since we did not have a control group in this study, it is not possible to generalize these findings beyond the participating group.

Table 13.8 presents an illustrative example of the range of student responses related to visualization three in chapter one of our VIT. We selected these responses because this is the one prompt to elicit student responses across the five levels of interpretation.

Table 13.8 Five levels of interpretation of visualization three: candle, pie plate with ice cubes

Prompt 3 – Describe in the box below what you think is making the spiral move in the pie plate video	
Qualitative description of level	Example of student response at level
Level 1 – when asked to interpret a representation of a physical phenomenon, the student(s) focuses on the physical features of the phenomenon only.	**Its moving** (student 21).
Level 2 – when asked to interpret a representation of a physical phenomenon, the student(s) focuses on the physical features of the phenomenon and adds some mention of observable causes (e.g., wind, the candle, the ice).	I think what is making the spiral move in the video is that when **the candle is under** it the spiral slows down and when the candle isn't there then the spiral speeds up (student 8).
Level 3 – when asked to interpret a representation of a physical phenomenon, the student(s) focuses on the physical features of the phenomenon and adds some mention of observable causes (e.g., wind, the candle, the ice) and some mention of unobservable causes (heat, cold).	I think what's making the spiral move is the ice in the plate and the candle **because the ice is cold and the candle is hot and both together make the spiral able to move.** I know that hot air and cold air mix together make it to have motion, I think if they didn't have the candle below the spiral, just with the ice in the pie plate the spiral wouldn't move, the ice would just melt in the pie plate, but like they have the candle it's moving!. As you see in the video when the women moves the candle the spiral stops moving, and when the candle is their the spiral is moving (student 4).
Level 4 – when asked to interpret a representation of a physical phenomenon, the student(s) focuses on the physical features of the phenomenon and adds some mention of observable causes (e.g., wind, the candle, the ice) and some mention and elaboration of systematic linkages in unobservable causes (condensing, water to gas).	When the lit candle was placed underneath the spiral it moved counter-clockwise also the spiral was moving upward towards the cool ice plate, **when the spiral was moving up it had no more room to go up because of the cool air from the ice plate. Allison notice when the lit candle was removed from underneath the candle the spiral was moving clockwise and spreading more down because the cooler air was pressing the spiral to the warm air** (student 3).
Level 5 – translating or referring to a different representation in explaining current one.	The heat from the candle, and the ice in the plate combine which **makes it spin because hot and cold air makes a tornado, and the spiral is basically the tornado.** Then when you take out the candle it starts spinning in the opposite direction, because its only the cold air (student 14).

13.6 Discussion

Our results indicate that students used the visualizations to scaffold one another's conceptual understanding of the process of convection. They did this, in part, through cross-referencing visualizations which is evidence of the efficacy of our designed system based on the theories of Gilbert (2008) and Ainsworth (1999, 2006). We found that students' used the 2D visualizations to help them reason about the 3D visualizations (for example, using the 2D Hadley cell and the global convection sphere diagrams to reason about the movement of air in the 3D visualization of the thunder cloud – see Table 13.2). This finding is consistent with Gilbert's (2008) explanation of learning with dimensional visualizations. As noted above, Gilbert argues that student understanding of phenomena is supported by visualizations that begin with their 3D experiences of the real world and is further developed and supported by the use of finer grain 2D visualizations of the same phenomenon. Finally, as students' knowledge advances they are able to reason with a 1D representation of the problem. Our VIT presented a mixture of 3D and 2D visualizations to help students develop a basic understanding of the phenomenon of convection.

Moreover, as consistent with the theories of Ainsworth (1999, 2006) it appears that the complementary visualizations presented throughout the VIT may have helped students develop a deeper understanding of the concept of convection. For example, the first three visualizations in chapter one of our VIT included a 3D video of a real life thundercloud forming, a 2D photographic representation of the process of convection in water (hot (red dye) and cold water mixing), and finally a video of the pie plate, paper, candle experiment, which is both a 3D representation of real life experience and a 2D representation of the macro phenomenon. If we look at student responses to question prompts on the researcher journal, we see that question number three, related to the pie plate experiment resulted in the largest number of level three responses. In other words, students wrote the most explanatory answers in relation to the pie plate video. This video clearly demonstrates how the heat from a candle will make the paper move in a certain direction, and, when the candle is removed, the cold from the plate will make air move in the opposite direction. It is possible to interpret these findings as evidence that the mixture of 3D and 2D visualizations assisted students in developing their understanding of the phenomenon.

In addition to students using the visualizations to scaffold their own and their partners' understanding, we also found that the teachers used the visualizations to prompt students' metacognitive reflection. These results are encouraging. The visualizations could have been deployed didactically, with the teacher calling student attention to relevant aspects of the visualizations and/or simply providing facts. But, instead, the teachers in this study were more likely to prompt the students to think about what they were seeing in terms of their own prior knowledge, their previous studies with the teacher, and/or in terms of the other representations. In this way, the teachers guided students to reflective engagement with the visualizations themselves. They promoted students' active learning with the visualizations. Prior research has shown that metacognitive reflection in simulated environments results in higher levels of student learning (Azevedo & Cromley 2004; Azevedo et al. 2004). The findings in this section are consistent with the work of Li (2012) and Shear and Penuel (2010), both of whom argued that teachers tend to shift their pedagogical approach to scaffolding student inquiry when they themselves are involved in the design and creation of the visualization environment, as our teacher participants were.

Despite these encouraging results, we also found that students tended to interpret the representations at low levels; 71% of the responses on the student journals were coded as a level one interpretation. Students primarily described the physical elements of what they were seeing, but they did not tend to go beyond this description. As noted above, it is possible that students simply did not exert themselves in completing the researcher journal because there was no assessment aspect connected to it. However, there are two other possible explanations for these low level responses. First, many of our prompts may have been worded too vaguely to elicit high-level responses. For example, the first prompt, related to the time-lapse video of the formation of a thundercloud simply asked students to *describe* what they saw. Most of the students provided a physical description. However, when we asked for causal interpretations, for instance in prompts three and eight, the majority of student responses were at the higher end of interpretation (level three and above). That said, some students did provide higher-level responses to the vague prompts and lower level responses to causal prompts, which leads us to the second possible explanation for low levels of interpretation of the representations: low levels of student understanding of the phenomenon. This last interpretation is supported by the pretest results.

Indeed, we noticed that some of the higher-level responses showed evidence of student misconceptions related to convection. For example, in reply to prompt three, a student who presented a level three answer, by referring to the unseen forces of heat and cold on the movement of the spiral, also indicated that hot air and cold air cannot mix. In this response, the student has shown a fundamental misunderstanding of the process of convection. Indeed, only a few students demonstrated a clear understanding of the process of convection and the role of the rotation of the earth in creating weather patterns. Given the brief duration of our intervention, it is likely that these few students had a strong understanding of these topics prior to engaging with our VIT.

However, given the fact that the students, overall, raised their scores from the pretest to the posttest, it is also likely that, misconceptions notwithstanding, the students did improve their understanding of the process of convection at a broad level. Evidence of student cross-referencing the visualizations helps to explain this outcome. As students were exposed to a number of visualizations of the process of convection, they were able to repeatedly and flexibly consider how the process unfolds. In many cases, the students were able to connect what they were seeing with the well-known phrase ‘hot air rises’. Many students used this very explanation for much of what they were seeing in chapter one of the VIT. In viewing multiple representations of the phenomenon of convection, the students were, arguably, able to build a more robust understanding of what diSessa (1988) might call a phenomenological primitive (p-prim). A p-prim is defined as a way of knowing the world from experience that results in an intuitive, explanatory framework for thinking and reasoning about the experienced world. While the trope ‘hot air rises’ may be more of a linguistic phenomenon, in other words, it is likely that students may have heard adults use the term to describe certain 'felt' environmental conditions, the trope does become a part of how students see the world and it governs their understanding of the phenomenon of convection. Because students already have some notion about the idea that 'hot air rises,' our efforts to broaden students' thinking about the phenomenon has, potentially, expanded their understanding of the process of convection and provided more of a platform for them to build on in future physics classes. In other words, our brief intervention may have succeeded in laying the groundwork for future, meaningful learning about convection.

13.7 Conclusion

While our intervention was brief and, primarily exploratory, it does appear that students developed their knowledge of the process of convection and the role of the rotation of the earth on global weather patterns. A limitation of our study is the disappointingly low levels of reliability found for our posttest and the analysis of the electronic journals. Despite these instrumentation issues, our research did allow us to learn more about how the VIT may be meaningfully deployed by the teachers. Our teachers were involved in the development of the VIT environment. They worked with the researchers to create an environment that would facilitate and scaffold student learning. The teachers then actively guided students to engage with the visualization in meaningful ways through conceptual, metacogntive, and representational scaffolding. Rather than simply explaining the phenomenon or representation in a didactic fashion, the teachers used the visualizations to scaffold students' learning and engagement. This is an ideal approach to teaching with multiple representations because it supports future learning with such materials. If students are supported in their engagement, they have a greater chance of making sense of other visualizations and representations at a later time. Again, this pedagogical approach of scaffolding aligns with both Gilbert's (2008) and Ainsworth's (1999, 2006) notions of representational competence and its relationship to scientific reasoning. The more students are supported to understand the various representations at the various dimensional scales (3D and 2D), the better their understanding will be. At this point, future research that includes a longer intervention period with our VIT is warranted. Moreover, to improve our understanding of the efficacy of our VIT, it would be useful to conduct laboratory studies devoted to examining the sequencing of 3D vs. 2D representations, as well as the utility of particular types of representation. Based on the researcher journal results, it seems that videos that depict 3D, real life phenomenon led to more sophisticated responses by students. While the 2D representations garnered simple replies that focused on physical descriptions of the phenomenon. Hence, it may be important to present more 3D representations and/or to develop 2D representations that overlap more with 3D representations to further scaffold understanding of the micro processes driving the macro processes of convection.

Overall, our data indicated that students were able to meaningfully engage with the visualizations, scaffold one another's knowledge, and co-construct understandings from cross-referencing the various 3D and 2D depictions of the process of convection. Moreover, we found that teachers used the pedagogical strategy of metacognitive prompting in their interactions with students around the visualization. This finding has interesting implications for the design of future online systems. If teacher participation in the design of a virtual system results in important pedagogical shifts, in this case from didacticism to metacognitive prompting, then designers of virtual systems would do well to build authoring tools and activities into the designs of their own systems that would encourage and empower teachers to act as designers within the system. Furthermore, teacher education programs may wish to add the creation and use of specific representations for teaching science as an aspect of science teachers' preparation. Future research should follow up on the impact of teachers as designers of visualizations on the pedagogical approaches they employ when using those visualizations in science teaching.

Appendix A

Researcher's Journal

Section 1.1 – Thunderstorm Formation

Directions: Describe in the box below what you think is happening in the video:

Section 1.2 – Hot and cold water with red dye

Directions: Describe in the box below step-by-step what is happening in the red dye video:

Section 1.3 – Candle, pie plate with ice cubes

Directions: Describe in the box below what you think is making the spiral move in the pie plate video.

Section 2.2 – National Weather Report

Directions: Write one sentence in the box below about the direction the weather systems are moving.

Section 2.3 – Global Convection Currents

Directions: List at least three observations about the movement of weather systems globally.

1.

2.

3.

Section 2.4 – Create a hypothesis of why the patterns you see do not match what would occur if convection currents were the only forces moving air around earth. Write your hypothesis in the box below:

Section 2.5 – Temperature Data Animations

Directions: How might the animations of convection currents help meteorologists predict the weather? Write two examples here:

1.

2.

Section 2.6 – Virtual Fluid Experiment

Directions: Compare the temperature patterns in the virtual experiment from a high rotation rate (around 4 secs per rotation) experiment with a low rotation rate experiment (around 25 secs per rotation).

Record the parameters of your experiments in the tables provided here:

Experiment #1	
Rotation Period (secs)	
Temperature difference (degrees centigrade):	20

Experiment #2	
Rotation Period (secs)	
Temperature difference (degrees centigrade):	20

Paste the experiment images below:

Experiment #1

Experiment#2
Compare the images created by the two experiments.
Make two observations about the differences in these images:

1.

2.

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