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.

J. Airey (✉)
Physics Education Research Group, Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden

Department of Mathematics and Science Education, Stockholm University, Stockholm, Sweden
e-mail: john.airey@physics.uu.se

C. Linder
Department of Physics, University of the Western Cape, Cape Town, South Africa

Physics Education Research Group, Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden
e-mail: cedric.linder@physics.uu.se

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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

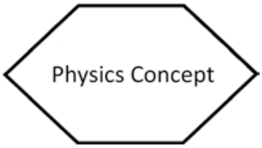


Fig. 5.1 Disciplinary concepts have multiple aspects. Here we see an *idealized* hypothetical representation of a physics concept using a *hexagon*. Each side of the hexagon represents one distinct aspect of the physics concept

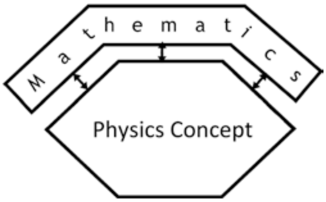


Fig. 5.2 In this case, using a mathematical resource affords access to three aspects of the physics concept

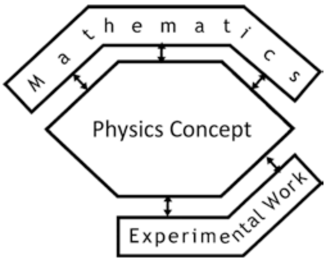


Fig. 5.3 Experimental work affords access to two further aspects of the physics concept

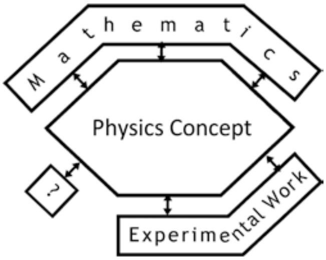


Fig. 5.4 Complete constitution of the physics concept is still impossible for students without access to the sixth aspect. Here the semiotic resource that gives access to this final aspect is marked with a question mark

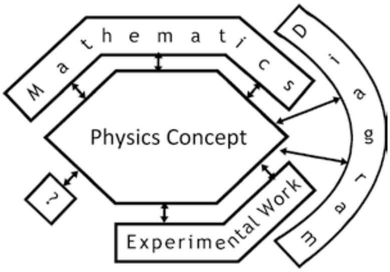


Fig. 5.5 The introduction of a diagram fails to represent the missing aspect (question mark) but does provide a transductive link between the mathematical and experimental resources

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.

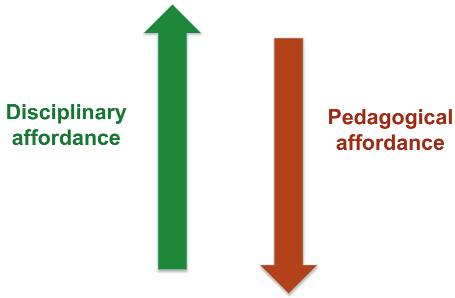


Fig. 5.6 The relationship between disciplinary affordance and pedagogical affordance
Disciplines leverage the disciplinary affordances of highly specialized semiotic resources in order to make meaning. These semiotic resources function as a type of "disciplinary shorthand". An increase in pedagogical 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

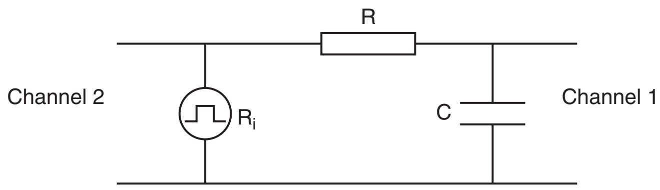


Fig. 5.7 Circuit diagram (taken from the laboratory notes)
Note: Students were asked to connect this circuit, however, the connections for signal and ground are not shown

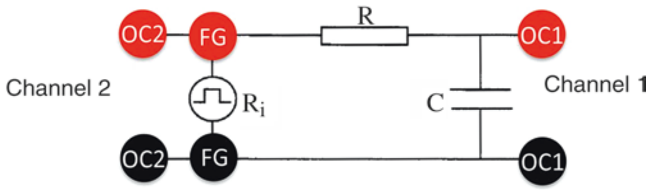


Fig. 5.8 Increasing the pedagogical affordance
The disciplinary affordance of the intended circuit unpacked by addition of *coloured dots* (*red* for signal, *black* for circuit ground). *OC* oscilloscope input channel and *FG* function generator output. This circuit shows the oscilloscope measuring 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

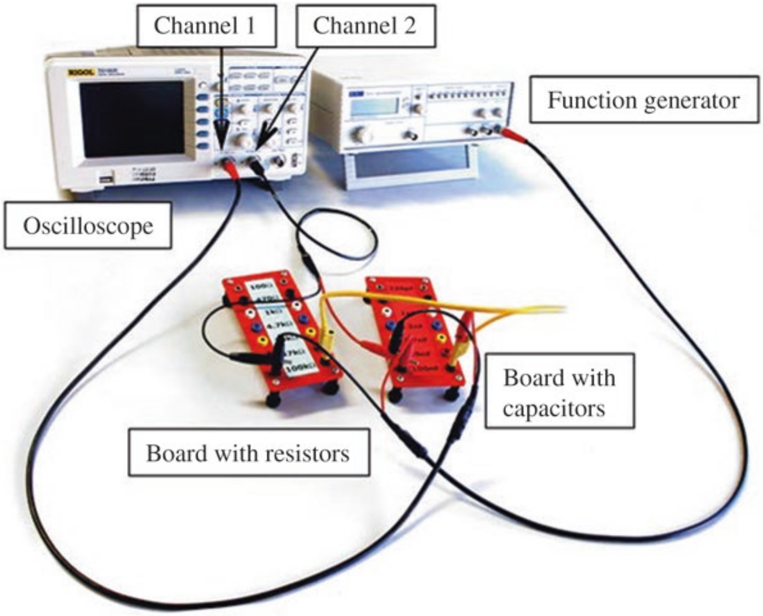


Fig. 5.9 Incorrect physical circuit made by students
The reason the circuit is incorrect cannot be seen by referring to the original diagram in Fig. 5.7

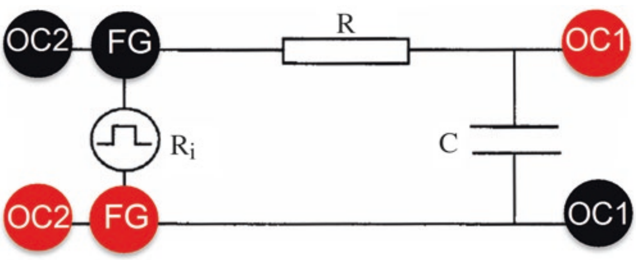


Fig. 5.10 Incorrect student circuit represented using the unpacked semiotic resource
Note: Here it is now possible to discern short-circuits in the connections. These are not visible using the diagram in Fig. 5.7

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.

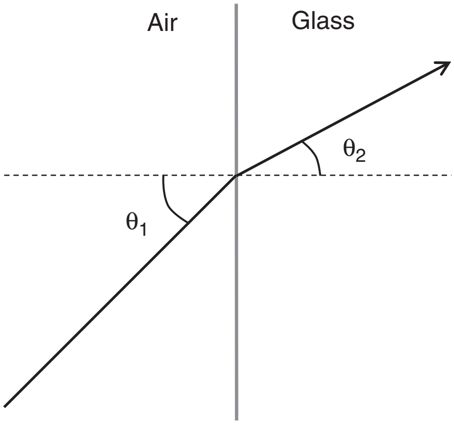


Fig. 5.13 A typical ray diagram of the refraction of light
Disciplinary relevant aspects direction, medium and angle are visible but the speed of light is not visible

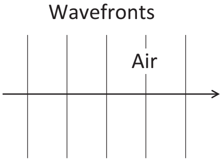
three of the required disciplinary relevant aspects. In Fig. 5.14, direction is shown by an arrow, medium is denoted by labels together with a boundary line and speed is represented as proportional to the distance between wavefronts (similar to the way dots on tickertape can be used to indicate speed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

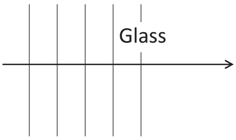
Next, in order to connect the distance between wavefronts to speed of light, students are asked to predict whether the wavefronts will be closer together or further apart in glass, leading to them generating diagram (c) with wavefronts for glass. These two diagrams can then be combined in (d) to highlight 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.

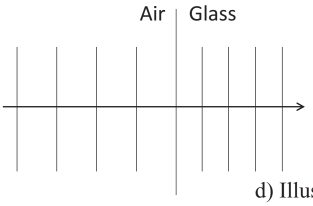
a) Direction



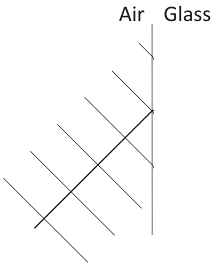
b) Wavefronts in air (separation proportional to speed)



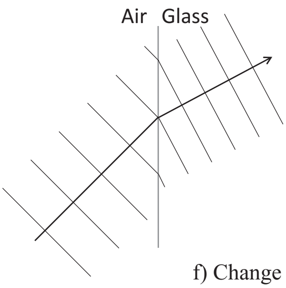
c)Wavefronts in glass (separation proportional to speed)



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

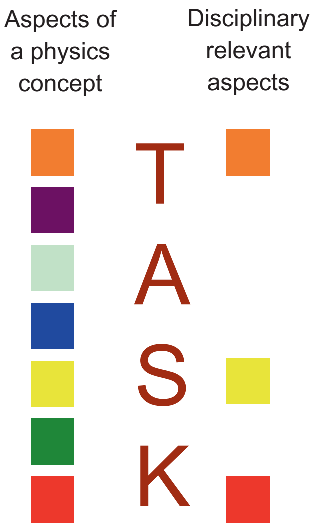


Fig. 5.15 Disciplinary relevant aspects for a given task
Illustration of the range of disciplinary aspects (*coded as colours*) that together make up a (hypothetical) physics concept, showing the disciplinary relevant aspects that the task calls for—the sub-set required for a performing a particular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

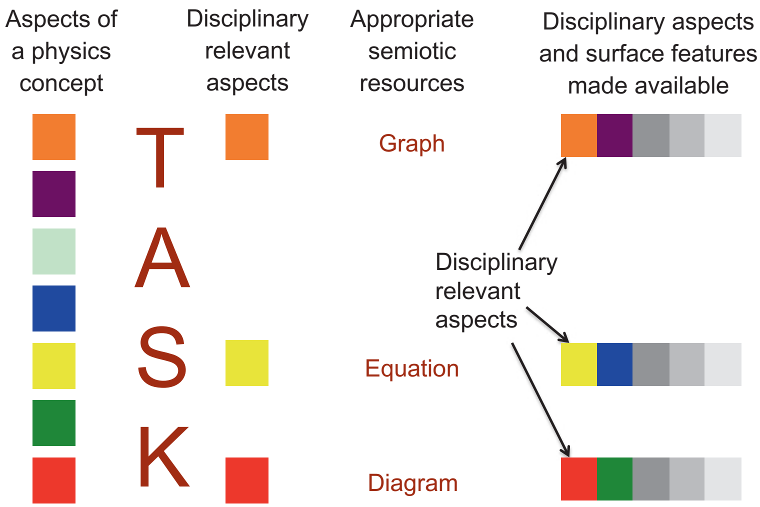


Fig. 5.16 Choosing the appropriate semiotic resources
In this case the combination of three semiotic resources (graph, equation and diagram) is needed in order to provide access to the disciplinary relevant aspects for the task. However, each of these semiotic resources also presents other disciplinary 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).

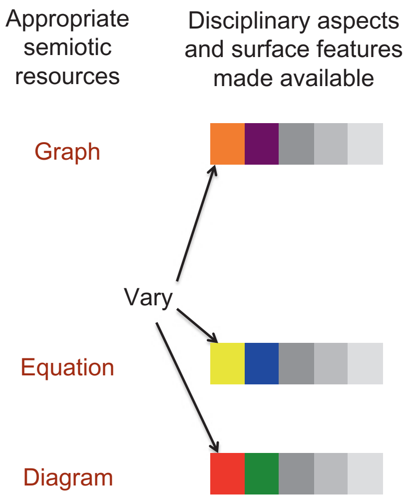


Fig. 5.17 Using variation to help students to discern the disciplinary relevant aspects
In order to facilitate discernment, each of the disciplinary relevant aspects needs to be varied whilst holding all other aspects and surface features constant

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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