A Disciplinary Discourse Perspective on University Science Learning: Achieving Fluency in a Critical Constellation of Modes

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Abstract: In this theoretical article we use an interpretative study with physics undergraduates to exemplify a proposed characterization of student learning in university science in terms of fluency in disciplinary discourse. Drawing on ideas from a number of different sources in the literature, we characterize what we call "disciplinary discourse" as the complex of representations, tools and activities of a discipline, describing how it can be seen as being made up of various "modes". For university science, examples of these modes are: spoken and written language, mathematics, gesture, images (including pictures, graphs and diagrams), tools (such as experimental apparatus and measurement equipment) and activities (such as ways of working—both practice and praxis, analytical routines, actions, etc.). Using physics as an illustrative example, we discuss the relationship between the ways of knowing that constitute a discipline and the modes of disciplinary discourse used to represent this knowing. The data comes from stimulated recall interviews where physics undergraduates discuss their learning experiences during lectures. These interviews are used to anecdotally illustrate our proposed characterization of learning and its associated theoretical constructs. Students describe a repetitive practice aspect to their learning, which we suggest is necessary for achieving fluency in the various modes of disciplinary discourse. Here we found instances of discourse imitation, where students are seemingly fluent in one or more modes of disciplinary discourse without having related this to a teacher-intended disciplinary way of knowing. The examples lead to the suggestion that fluency in a critical constellation of modes of disciplinary discourse may be a necessary (though not always sufficient) condition for gaining meaningful holistic access to disciplinary ways of knowing. One implication is that in order to be effective, science teachers need to know which modes are critical for an understanding of the material they wish to teach.

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Introduction: characterizing learning in terms of discourse

One person does not constitute a discipline. Every discipline has been built up and sustained by many thousands of individuals, each playing their own roles in creating the shared ways of knowing that make up the discipline. By shared ways of knowing we mean here the coherent system of concepts, ideas, theories, etc. that have been created to account for observed and theoretical phenomena. What allows these individuals to share and refine their disciplinary ways of knowing is the system of semiotic resources they develop to represent this disciplinary knowledge. This is not a new idea. In the early seventies cultural critics such as Postman and Weingartner (1971) pointed out that "A discipline is a way of knowing, and whatever is known is inseparable from its symbols (mostly words) in which the knowing is codified" (p. 103). For science, Lemke (1998) has claimed that this semiotic system consists of "…words, images, symbols, and actions" (p. 4). One way, which we adopt, of collectively referring to this whole system of semiotic resources is to use the term discourse.

The argument that the ways of knowing that constitute a discipline are inseparable from their discursive representations has led to the suggestion that a significant part of learning may be regarded as "discovering" the meaning of the discourse employed by a discipline through participation (Kuhn, 1962/1996; Northedge, 2002, 2003; Östman, 1998). For example, Kuhn (1962/1996) makes the following claim:

> If, for example the student of Newtonian dynamics ever discovers the meaning of terms like 'force', 'mass', 'space', and 'time', he does so less from the incomplete though sometimes helpful definitions in his text than by *observing and participating in the application of these concepts* to problem-solution' (pp. 46-47 Emphasis added).

Further, Northedge (2002) argues that "We encounter [words] embedded within discourse, and come to apprehend their meaning in the process of participating in the discourse which generates them" (p. 257). Learning may then be characterized as coming to experience disciplinary ways of knowing as they are represented by the disciplinary discourse through participation.

Following Fairclough (1995), the New London Group (2000) argue that each "semiotic domain" has its own specific "order of discourse" that is "a structured set of conventions associated with semiotic activity (including use of language) in a given social space" (p. 20). In this article we interpret this in terms of each discipline having its own unique order of discourse, so that the order of discourse of, say, art history, will be radically different than the order of discourse of physics.

It has been shown, however, that such disciplinary orders of discourse are often taken for granted by university lecturers in their teaching (Middendorf & Pace, 2004; Tobias, 1986, 1992-1993). In this respect, Northedge (2002) believes university lecturers often do not fully appreciate "…the sociocultural groundings of meaning. Their thoughts are so deeply rooted in specialist discourse that they are unaware that meanings they take for granted are simply not construable from outside the discourse" (p. 256). In a similar vein, a number of authors have made the case that challenges found in student learning are largely a function of difficulties in handling and understanding highly specialized forms of communication that are not found to any great extent in everyday situations, for example, Driver & Ericksson (1983), Solomon (1983), Säljö (2000), and diSessa & Sherin (2000). Learning is thus increasingly being characterized in discourse terms (for example diSessa, 2004; Florence & Yore, 2004; Lemke, 1990, 1995, 1998; Northedge, 2002, 2003; Roth, McGinn, & Bowen, 1996; Swales, 1990; Säljö, 1999; Wickman & Östman, 2002).

In this article we draw on a variety of published work, such as that of Lemke (1990; 1995; 1998), Kress, Jewitt, Ogborn & Tsatsarelis (2001), Duval (2002; 2006), and diSessa (2004), in order to craft a concept that we call disciplinary discourse (the complex of representations, tools and activities of a discipline). What we bring to earlier work is the suggestion that students need to become fluent in a critical constellation of the different semiotic resources—or *modes* of disciplinary discourse as we depict them—before they can appropriately holistically experience the disciplinary way of knowing that these resources/modes potentially give access to. In support of our proposal we anecdotally illustrate our ideas using learning-experience data situated in university physics. Since our data comes from student learning during lectures, it best illustrates the representations aspect of disciplinary discourse (see Figure 1).

Disciplinary discourse: a collection of modes

If we take the point of view that there are useful insights to be gained by characterizing learning in terms of discourse, then for the purposes of this article we first need to further unpack what we mean by such discourse.

Tsui (2004) recently defined discourse for the purposes of contemporary educational research work as "a process in which meanings are negotiated and disambiguated, as well as a process in which common grounds are established and widened" (p. 167). This definition fully encompasses our own view of disciplinary discourse; however, there is a risk that using such a definition can become unintentionally limiting. This is because the definition does not specifically challenge the somewhat traditional view that disciplinary discourse is synonymous with the specialized *language* used within a discipline. Such a language-based interpretation of Tsui's definition proves to be limiting when attempting to describe the order of discourse of university science, since it takes for granted, or ignores, other important representations such as diagrams, graphs and derived formulae.

Now Hall's (1997) view of discourse becomes a central pillar in our developing characterization of disciplinary learning. Here, discourse is viewed as a concept describing "…ways of referring to or constructing knowledge about a particular topic of practice: a cluster (or formation) of ideas, images and practices, which provide ways of talking about, forms of knowledge and conduct associated with, a particular topic, social activity or institutional site in society" (p. 6). This facilitates a further extension by drawing on Kress, Jewitt, Ogborn & Tsatsarelis (2001) to depict the discourse of a discipline as being made up of a number of modes, where spoken and written language are examples of two such modes for university science. Drawing on Gibson (1979) Kress and his colleagues suggest that each of these modes can be seen as having different *affordances* or, as we prefer to put it, different possibilities for representing disciplinary ways of knowing:

> Several issues open out from this starting-point: if there are a number of distinct modes in operation at the same time (in our description and analysis we focus on speech, image, gesture, action with models, writing, etc.), then the first question is: "Do they offer differing possibilities for representing?" For ourselves we put that question in these terms: "What are the *affordances* of each mode used in the science classroom; what are the potentials and limitations for representing of each mode?"; and, "Are the modes specialized to function in particular ways. Is speech say, best for this, and image best for that?" (Kress et al., 2001, p. 1)

This leads us to a construct which we call disciplinary discourse as a way to characterize this collection of modes. It is this disciplinary discourse that students are expected to engage with and make their own. In this spirit, we characterize disciplinary discourse as the complex of representations, tools and activities of a discipline. We will now describe each of these components in more detail.

Representations

By representations we mean those semiotic resources that have been designed specifically to convey the ways of knowing of science. This stems from the notion that in university science such a system of semiotic resources is made up of far more than simply the representational modes of oral and written language. Other modes such as images (e.g. graphs and diagrams), mathematics and gesture also play a central role in this system (Ainsworth, 2006; Givry & Roth, 2006; Kress & van Leeuwen, 2001; Roth, Tobin, & Shaw, 1997; Roth & Welzel, 2001) and are therefore included in our framework.

Tools

Every discipline has its own specialized physical tools or apparatus that its members draw on to create disciplinary ways of knowing, and, indeed, the scientific community excels itself in this respect. Thus, learning to use the physical tools of science can be regarded as an integral part of being able to *do* science. But there is another, perhaps less obvious characteristic of tools and apparatus. From a cultural-historical perspective it is possible to see a tool in terms of a condensation of meaning. Thus, for example, Wartofsky (1979) has argued that it is possible for a tool, in certain circumstances, to mediate the knowing that went into its production. In other words, appropriate student interaction with a physical tool can lead to more than a simple, situated understanding of how to do a piece of science—students may also gain access to some of the ways of knowing implicit in a given tool's development. An everyday example of this is a person using a claw hammer to knock in nails who discovers, through close examination of the hammer, the nail-extracting function of the claw end. One can imagine that historically, this part of the hammer developed out of a specific need in the working environment. Note here, that the discovery of the nail-extracting function could conceivably be made *before* the need to remove a nail arose. In such a situation, the tool itself would have taught the user something about the activity for which it was designed. We therefore believe that the tools of a discipline—though not explicitly designed to mediate scientific ways of knowing—must be included as a separate mode in any characterization of the semiotic resources of that discipline.

Activities

Similar to tools, the things that are done in the name of scientific activity need to be assimilated and learned by apprentices of the discipline. As with tools, these activities can be characterized in terms of condensations of meaning. Thus the ways of knowing that underpin the activities may be opened to students through participation and observation. (See for example Crawford, Kelly, & Brown, 2000; Kuhn, 1962/1996; Roth & Lawless, 2002; Wells, 2000). We believe that this idea is the leitmotif of student laboratory work. Thus we include activities as a further mode of disciplinary discourse.

The relationship between disciplinary ways of knowing and the system of modes that collectively make up disciplinary discourse is shown in Figure 1.

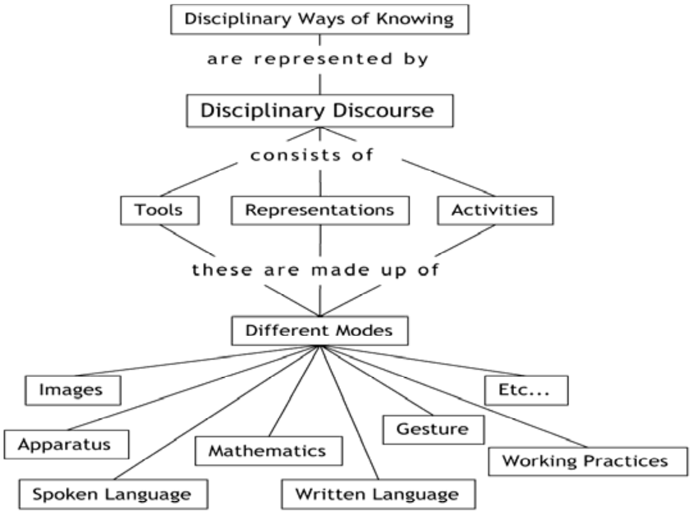
Disciplinary Ways of Knowing
are represented by
Disciplinary Discourse
consists of
Tools
Representations
Activities
these are made up of
Different Modes
Images
Etc...
Gesture
Apparatus
Mathematics
Working Practices
Spoken Language
Written Language

Figure 1.
Diagram of the relationship between disciplinary ways of knowing and the modes of disciplinary discourse.

In our terms then, the modes of disciplinary discourse include not only the words, symbols, gestures, diagrams, formulae, etc. used by a discipline; but also the artifacts, pieces of apparatus, measuring devices, etc. and the actions, practices and methods residing within the discipline. We can therefore argue that the disciplinary discourse of university science serves a dual purpose; it is first and foremost the physical application of the ways of knowing of the scientific community—quite simply it is how we *do* science, and it is also the sole means we have of sharing and evaluating this knowing.

Why not use "Big D" Discourse?

In a number of respects our notion of disciplinary discourse is similar to Gee's (2005) notion of "big D" Discourses. Gee uses Discourse (with a capital letter) to designate the combination of discourse—that is language-in-use with other, non-language "stuff" (p. 20). The difference between Discourse and disciplinary discourse is that disciplinary discourse carries a much more focused meaning—being defined as the complex of representations, tools and activities of a discipline. Gee's Discourse is a much wider concept which also includes all the attributes of the learners themselves. Indeed, in contrast to our own view of disciplinary discourse as *representing* a particular way of knowing, Moje, Collazo, Carrillo & Marx (2001) in the following quote appear to suggest that Discourse *is* a particular way of knowing: "Any stretch of language (discourse) is always embedded in a particular way of knowing (Discourse)…" (p. 470). For a good illustration of the Discourse approach the reader is referred to Kittleson & Southerland (2004) who use the concept to analyze engineering students' group knowledge construction. Thus Gee's Discourse can be characterized, in relation to social identity, as including such things as students' epistemology, group dynamics, gender, social status, etc. These aspects, whilst certainly important in student learning, are purposefully not part of our constitution of disciplinary discourse. Our reason for excluding such important aspects is that we are arguing for analyzing the system of semiotic resources, in terms of modes of disciplinary discourse, that a discipline offers students. Clearly, without appropriate access to these semiotic resources (or, as we characterize it, fluency in these modes) learning disciplinary ways of knowing becomes impossible, regardless of any student-specific factors.

Appresentation and facets of a way of knowing

DiSessa (2004) has suggested that scientists are designers of representations, claiming that "the invention of representations constitutes a fundamentally important class of advances" (p. 296). New representations give scientists the ability to view disciplinary ways of knowing in new ways. These specialized functions of representations have been discussed and categorized by Ainsworth (1999; 2006). From our disciplinary discourse perspective we can say that the modes of disciplinary discourse have different possibilities for representing disciplinary ways of knowing, and thus each mode has certain potentials for revealing and providing access to particular *facets* of a given way of knowing. By facets we mean the various attributes of a disciplinary way of knowing which are necessary for constituting a broader and richer experience of that way of knowing. An illustration of these facets of a way of knowing can be seen in the modes used in the teaching and learning of Ohm's law. A student may experience facets of Ohm's law via a number of different modes, for example, current-voltage relational representation through the use of: circuit diagrams, oral descriptions, written descriptions, demonstrations, hands-on activities (with batteries, wires and bulbs), a table of voltages and currents for a given circuit, the mathematical formula **V=IR** and its graphical illustration. Each of these modes potentially brings certain facets of Ohm's law to the fore, whilst others remain in the background or simply are not present. It is thus only through combining a number of these modes that a holistic experience of the disciplinary way of knowing we call Ohms law can be constituted (analogous to viewing a physical object from different angles). Thus, typically a disciplinary way of knowing may only be partially represented by one particular mode of disciplinary discourse (or even more than one in certain cases). This relationship is illustrated in a highly simplified and idealized manner in the Figures 2 through 6.

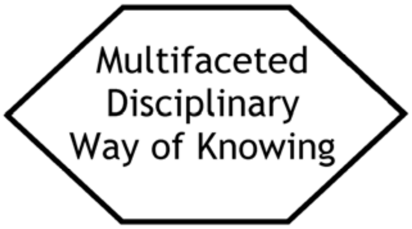

Figure 2.
Disciplinary ways of knowing have multiple aspects or as we term them facets. Here we have an idealized representation of a disciplinary way of knowing using a hexagon. Each side of the hexagon represents one facet of the disciplinary way of knowing.

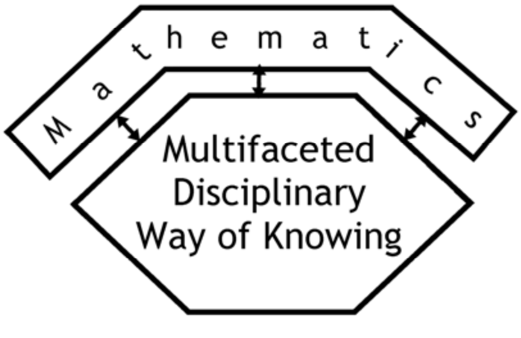

Figure 3.
In this case, representation using the mathematical mode of disciplinary discourse allows access to three facets of the disciplinary way of knowing

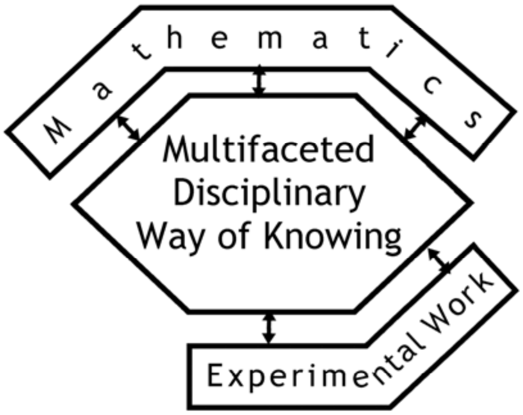
Mathematics
Multifaceted
Disciplinary
Way of Knowing
Experimental Work

Figure 4.
Experimental work allows access to two further facets of the disciplinary way of knowing.

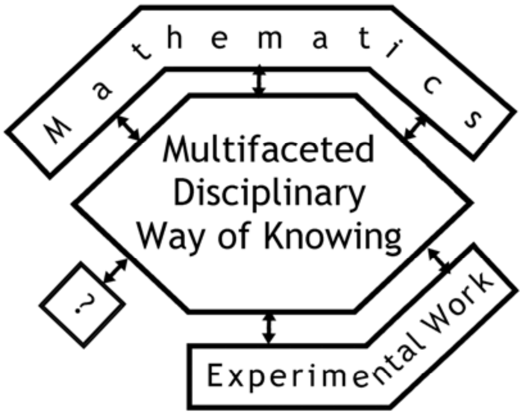
Mathematics
Multifaceted
Disciplinary
Way of Knowing
?
Experimental Work

Figure 5.
Complete constitution of the disciplinary way of knowing is still impossible for students without access to the sixth facet. Here we have chosen to label the mode which gives access to this final facet with a question mark, highlighting what we believe is the present situation in university science, where we know little about the particular constellation of modes which are needed to give appropriate holistic access to any given disciplinary way of knowing.

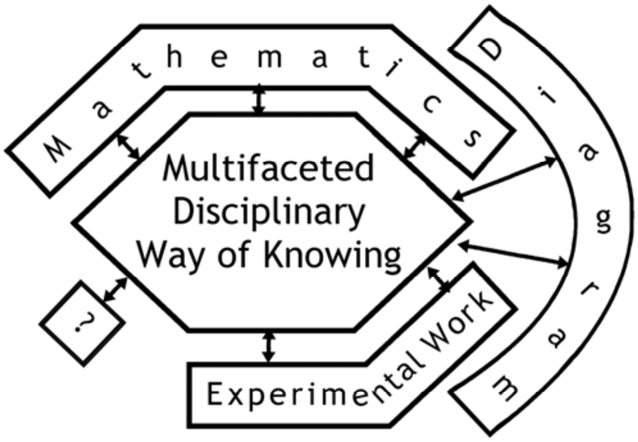

Figure 6.
In this final figure, the visual mode is added in the form of a diagram. In this particular case, the addition of the diagram provides a link between the mathematical and the experimental modes, but complete holistic constitution of the disciplinary way of knowing is still impossible.

In Figure 2, a hypothetical disciplinary way of knowing has six separate facets. These are represented by the six sides of a hexagon (Note: in reality disciplinary ways of knowing will have many more facets and the picture will be much more complex in nature). It is possible to represent three of these facets using the mathematical mode (Figure 3), whilst two further facets may be represented through the experimental mode (Figure 4). The sixth and final facet needed for a complete constitution of the disciplinary way of knowing is only available through a mode other than mathematics or experimental work. In Figure 5, we have chosen to use a question mark to denote this mode since we feel this reflects the present situation in university science where we actually know very little pedagogically about the constellation of modes needed for complete representation of disciplinary concepts. In Figure 6, the addition of a diagram fails to represent this missing facet, but does provide a link between the mathematical and experimental modes.

The relationship between modes of disciplinary discourse and disciplinary ways of knowing can be seen to be been discussed by Marton & Booth (1997) who posit that an appropriate experience of a disciplinary way of knowing will depend on the phenomenological concept of appresentation.

> When we have a perceptual or sensuous experience of something, which is to say we see, hear or smell it, we can talk about the mode in which it presents itself, that is, the way in which it appears to one or more of our senses. But in addition to what is "presented" to us—that is what we see, hear, smell—we experience other things as well.

> If we look at a tabletop from above, for instance, we hardly experience it as a two-dimensional surface floating in the air, in spite of the fact that what we see is, strictly speaking, a two-dimensional surface separated in some mysterious way from the ground. But in looking down on a tabletop we experience the legs that support it as well, because the experience is not of a two-dimensional surface, but of a table… That which is not seen, is not even visible is appresented … We wish to apply the concept of appresentation to experiences of abstract entities as well as concrete ones. If we think of the gravitational constant, g, for instance, then the highly abstract formulation made by Newton of how bodies affect one another at a distance is appresented, given that we have acquired sufficient education in and experience of classical physics (pp. 99-100).

For the purposes of this article, we can think of appresentation as the ability to spontaneously infer the presence of further facets of a disciplinary way of knowing over and above those made available through the mode a student has been presented with. One mode of disciplinary discourse opens up the possibility to experience a particular number of facets of a disciplinary way of knowing, but, in order to holistically experience this way of knowing, the other facets of the way of knowing need to be appresent. We therefore argue that learners of the discipline may be unable to fully experience a disciplinary way of knowing until two criteria are met. First, at some stage they must have experienced each of the various facets of the way of knowing. This we argue entails multimodal representation. Second, they need to be able to experience these facets simultaneously—that is when one facet or group of facets is presented to them through a particular mode of disciplinary discourse, the other necessary facets need to be appresent. We suggest this second criterion can only be met after students have familiarized themselves with each of the relevant modes of disciplinary discourse to such an extent that experiencing the various facets simultaneously becomes second nature, or as we term it, when they have become *discursively fluent* in a critical constellation of modes.

Discursive fluency

Following our earlier discussion of Fairclough's (1995) order of discourse, we constituted the notion of discursive fluency. By discursive fluency we mean a process through which handling a mode of disciplinary discourse with respect to a given disciplinary way of knowing in a given context becomes unproblematic, almost second-nature. Thus, in our characterization, if a person is said to be discursively fluent in a particular mode, then they come to understand the ways in which the discipline generally uses that mode when representing a particular way of knowing. Taber (2002) suggests such "familiarization" is needed because: "…the logical structure needed to develop the new ideas may exceed the processing capabilities of the student. Although each step in an explanation may itself be manageable, the overall structure may 'swamp' the student and seem much too complicated" (p. 73). Whilst the individual processing capabilities of students is not the focus of our particular description of learning in university science; the point that students often feel swamped by new material which they most likely will later experience as straightforward is obviously a valid one. Thus, we suggest that a degree of discursive fluency may be necessary before some of the facets of a disciplinary way of knowing that are made available by a given mode of disciplinary discourse can be appropriately related to the whole.

In this respect there is always the possibility that discursive fluency may not necessarily lead to an appropriate experience of the related facets of the disciplinary way of knowing—students might simply learn to *imitate* the order of discourse of a discipline. Clearly if students are imitating the order of discourse, then they will encounter difficulty when they are required to use disciplinary discourse in a creative way in unfamiliar situations. We further develop this discourse imitation argument as we progress with our proposal.

The multimedia effect

Before we move on to illustrate our disciplinary discourse construct from carefully selected anecdotal data, we feel it is necessary for us to briefly discuss the differences between our approach and the great deal of closely related work which has been carried out into what can be characterized as "multimodal teaching and learning". A comprehensive overview of work in this area can be found in Ainsworth (2006). As Reimann (2003) points out, two important ideas in this area are dual-processing theory (J. M. Clark & Paivio, 1991; Paivio, 1986) and cognitive load theory (Chandler & Sweller, 1991).

Dual-processing theory posits that the human brain has separate processing systems for visual and verbal input. This notion has been exploited by Mayer (1997; 2003) who describes a multimedia effect—that is students learn more deeply from words and pictures than from words alone. Cognitive load theory, however, posits that human processing ability is extremely limited, thus creating an upper limit to any multimedia effect (Miller, 1956). A selection of papers by leading researchers in this area of multimodal research was presented in a recent special issue of *Learning and Instruction* (volume 13, 2003). A common factor in the approaches described is a "snap-shot" interest in the most efficient method for communicating a certain "message" given the assumed limited processing capacity of the brain and the possibility of dual processing channels.

In contrast, our own interest in the modes of disciplinary discourse focuses on the longer-term goal of appropriately experiencing the ways of knowing of a discipline in a holistic way. This, we argue, can only be achieved through the kind of continued practice which eventually leads to discursive fluency in a number of modes. Moreover, as we have already outlined, the modes of disciplinary discourse are seen as offering different affordances, i.e. different possibilities for representing disciplinary ways of knowing. Thus it is this ability to more fully represent disciplinary ways of knowing through certain combinations of modes that is pertinent for our study rather than the learner's limited ability to simultaneously process input from a collection of modes.

Data

In Sweden, as in many countries, although English is not the first language, its use is commonplace in higher education. Language surveys of Swedish universities have revealed high proportions of English use, particularly in engineering, natural sciences and medicine. The anecdotal illustrations that we provide come from a larger study that qualitatively investigated how Swedish undergraduate physics students experience being taught physics in English and Swedish (Airey, 2006; Airey & Linder, 2006; 2007). In brief, this study involved two Swedish universities—one a larger, mainly research oriented university and the other a smaller, more teaching oriented university. Six complete physics lectures with different lecturers were video filmed. Each student in the study was present at two of these lectures as a part of their regular physics degree program, with both lectures taking place within a two-day period. Prior to filming, the lecturers teaching the courses had been interviewed about their aims for the lecture and how they saw these fitting into the "whole" for the students, their experiences of the given group of students as learners and any areas where they anticipated that the students could encounter problems with the material to be taught.

Twenty-two volunteer students were interviewed using both Swedish and English one to three days after the two lectures that they attended. These interviews were guided by a semi-structured interview protocol within a broad, open-ended approach. Each interview lasted approximately 1hr. 30mins.

Part of the approach we took was to ask students to talk about their experiences of learning physics by drawing on representations such as diagrams, text, oral descriptions and mathematics that they had encountered during their lectures. To do this, eight edited segments of video footage derived from the two lectures that the student attended, were shown to the interviewee students in order to create a stimulated recall environment (Bloom, 1953; Calderhead, 1981). Here our aim was to re-create as closely as possible the original learning situation, thus allowing students to better describe and reflect on their learning experiences in the specific situations that they were shown. All interviews were recorded digitally and fully transcribed.

It was while engaging with multiple viewings of the video material and many careful listenings to the interviews that we began to think about the ideas that we have brought together for this article. This later bought us to a refining and focusing phase that we centered around what we called "multiple modes of disciplinary discourse". To do this all of the digital interview files were "cut" into sections where students discussed similar themes in relation to given modes of disciplinary discourse. In order to help us efficiently build up an overall picture of what students were saying both as individuals and as a group, each of these sections was given a filename consisting of the topic discussed, the student's name and a five digit identification code which was in fact the excerpt's time stamp in the original master recording. It was then easy for us to either listen to all the excerpts dealing with a given mode or to select excerpts from a given student.

We followed this method mindful that it has been argued that the audio recording is a step further away from the interview itself, which is in turn several steps away from the actual learning experience in the lecture (c.f. Kvale, 1996; Säljö, 1997). At the same time we would argue that this approach had the benefit of better capturing the situatedness of the interview when we were working with the transcriptions. Maintaining this situatedness was considered important since in the interviews we were attempting, through stimulated recall, to vividly recapture for the students the essentials of their experience of being in a specific lecture. Student files could also be easily re-related to the whole of the interview due to the timestamp identification code we used which led us directly to the correct position in each master recording. Those sections of the interviews that were deemed relevant to the proposal we present in this article then became the object of an anecdotal data sub-study.

Supporting illustrations

The supporting empirical data we now present illustrates our proposed characterization of learning and its associated theoretical constructs. Since the students in the interviews are commenting on their experience of learning in lectures, where the sole purpose of the lecture is to communicate the ways of knowing of the discipline, the illustrations best depict those modes of disciplinary discourse that we have characterized as representations.

Discursive fluency through practice

The students in our study describe their learning of disciplinary discourse through a process we characterize as repetitive practice; using and reusing representations to solve multiple problem sets, and the reading and re-reading of lecture notes and prescribed textbooks. For example:

> Description 1: [You learn physics] by working with lots of problems—solving problems
> that's the way.

And here another student on the same theme:

> Description 2: …it's a combination of the teacher and the book and re-reading the notes.
> And some things, it can go one or two weeks and then ooh! It's like that!
> The penny's dropped!

We argue that we can view this kind of repetitive practice as an attempt to achieve discursive fluency. Note here that each of the modes of disciplinary discourse has a productive and a receptive version e.g. reading and writing, speaking and listening, etc. The term discursive fluency is not limited to production and can refer equally well to familiarization with a receptive version of a mode. We believe metaphorically that just as oral fluency in a foreign language is a product of repeated practice, the students in our study attain discursive fluency in the various modes of disciplinary discourse through a process that includes repetition—what Kuhn (1962/1996) has likened to "finger exercises" on the piano (p. 47).

Discursive fluency as a route to experiencing a disciplinary way of knowing

In our characterization, then, familiarization with the way meaning about a particular way of knowing is constituted in a particular mode gradually leads to discursive fluency in that mode. We further suggest that discursive fluency is a necessary condition for experiencing the associated facets of a way of knowing that the disciplinary discourse represents. In the following quotes students suggest that they use their discursive fluency (here in the mathematical mode) in order to experience facets of the ways of knowing of the physics discipline.

Description 3: Often I recognize the mathematical terms before I understand the physics. And then I apply the mathematics and try to do some problem-solving and then it all—not all but much of it—falls into place.

And here another student on the same theme:

Description 4: If I can see the mathematical connections with all the terms and variables then I can usually go back and see the physical part. So I go that way. First I go to the math and then I try to understand [the physics].

We interpret these statements in terms of students using their discursive fluency in the mathematical mode as a stepping-stone to experiencing some of the facets of a part of physics. In our characterization, these facets of the way of knowing that are accessible through the mathematical mode help these students to structure input into other modes and hence experience further facets of the disciplinary way of knowing. Now the chicken-and-egg question immediately arises: how does a student develop fluency in something that requires fluency? We propose that the facets that we have just described provide the answer. These facets could be described as acting like a "seed crystal" around which other representations can be collected and "decoded". Following our framework such decoding can itself only occur as students become fluent in these other modes of disciplinary discourse. This notion is supported by the observation that when discursive fluency is not present, students seem unable to holistically experience the associated facets of a disciplinary way of knowing. Similar ideas have been discussed by Duval (2002; 2006) who outlines the circumstances in which movement from one mathematical representation to another may either lead to increased student comprehension or a discontinuity in the learning process.

When students are not fluent in certain modes of disciplinary discourse

An illustrative example of a lack of discursive fluency is given below. In this section of a lecture the lecturer drew a diagram of a transformer on the board (Figure 7) and gave the following oral and written (underlined) description.

Lecturer : And now we will look at section 7.2.2 [in the textbook] which is about transformers. A transformer is just a device for transforming—that means

changing the value of either currents or voltages. [underlined text written on the whiteboard]
And concretely it looks like this.
[starting to draw Figure 7] You have a metallic core which has some permeability, μ. And as you will see it will be interesting to take ferromagnets—that means that μ is large. And we take two coils which are wound on this core, one is to the left and another one to the right. And let's assume that there is a current I_1 in the coil to the left and there are N_1 turns in this coil, and here we have N_2 turns and the current I_2

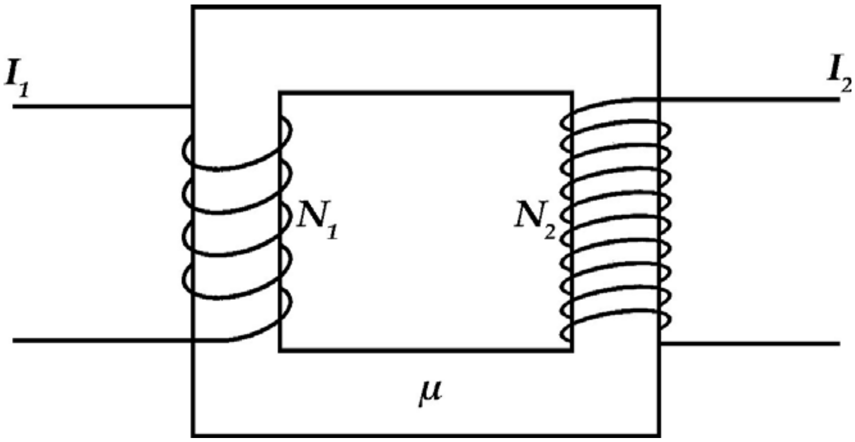

Figure 7.
Diagram of a transformer drawn by the lecturer on the whiteboard.

The following is the transcript of an interview with a student after having seen this short video clip during stimulated recall:

Interviewer: This is [the lecturer] starting this thing about transformers—what, what did you think about this particular part?
Student: Ummmh. Yeah, I don't know what this is. I didn't know what he was writing [on the whiteboard]…
Interviewer: Okay, he's drawing some kind of diagram, but you don't really know what that is that he's drawing or …?
Student: *No.*
Interviewer: Okay, so…
Student: —And I think it's, *it's, quite often like that in the lectures*—that he's drawing something on the whiteboard and he assumes that we know this from before.
Interviewer: So er, you—you've got, er, no idea what this transformer thing is?
Student: [laughing self-consciously] No!
Interviewer: What do you think makes this difficult to understand, then … just [personally] for you?
Student: [sighs] errm … errm—at first I think he should tell us what this is!

Our interpretation here is that this student has not had the necessary holistic learning experience of the facets of the way of knowing "described" by this combination of written and oral text and the disciplinary visual representation of a device for raising/lowering the EMF of an alternating current source. In the language of our proposed model, we would suggest that the interviewed student has not become discursively fluent with respect to this disciplinary way of knowing about the transformer vis-à-vis mutual inductance. This student was attending an intermediate-level course dealing with the principles of inductance, yet had not become appropriately proficient in seeing and handling this particular visual representation and thus little of the necessary appresentation is able to be evoked. Had the student instead answered something like, "The lecturer drew a diagram representing two solenoidal coils wrapped around an iron core so that equal amounts of magnetic flux could pass through each turn" then we could have inferred that this student was discursively fluent in this mode. Note, however, that this is not the same as saying that the student would then know what a transformer is. If the student has never seen an actual transformer, nor understood why changing voltages, currents and associated electric and magnetic fields could be of any interest, then discursive fluency—in this case simply knowing that this is a standard representation of a transformer—will not give the student a holistic access to the disciplinary way of knowing.

This piece of student transcript is a good illustration of Northedge's (2002) claim that some meanings cannot be construed from outside the discourse of the discipline. All the other students in this part of our study appeared to relate the diagram to a shared disciplinary way of knowing. As we discussed earlier, in phenomenological terms, the various facets of the way of knowing were appresent for them. Logically, however, there must also have been some stage when the diagram did not evoke this disciplinary way of knowing even for these students. At some stage in the past, these students learned to "see" something beyond the diagram, but now they (and the lecturer) take this meaning for granted—in our terms they have become fluent in the discourse of the discipline. We suggest that students will need to become fluent in a given mode of disciplinary discourse before they are able to experience the facets of the particular disciplinary way of knowing that that mode affords.

Necessary but not sufficient: Discourse imitation

If we accept that discursive fluency in a mode is necessary for experiencing the related facets of a disciplinary way of knowing, the next question is whether this discursive fluency is a sufficient condition for experiencing these facets. Put simply, does familiarization with a mode spontaneously lead to a student experiencing the associated facets of a disciplinary way of knowing? The iterations in our data analysis point towards discursive fluency being a necessary but not sufficient condition—that is students may learn to use a mode of disciplinary discourse appropriately, but still not experience the associated facets of a way of knowing. We use the term discourse imitation to characterize discursive fluency without a corresponding experience of the associated facets of a disciplinary way of knowing. This notion of discourse imitation is by no means new, being a theme which dates back to the ancient Greek and Roman rhetoricians and a commonly discussed factor in the contemporary teaching of academic writing (D. Clark, 1951; Mintock, 1995; Rider, 1990). This ability to use disciplinary discourse without experiencing the associated ways of knowing has in fact been documented by a number of researchers. For example, diSessa (1993) reports the following:

> One of the most striking findings from the interviewing studies on which this work is based is that 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" … these students' impressions of incomprehension are ironically more correct than their school assessments: They did not understand, even though they could perform (p. 206).

diSessa accounts for this phenomenon as follows:

> Symbolic and verbal propositions are prominent in instruction. It is possible to view these as being learned *prior* to the broader co-ordinations in intuitive knowledge that are eventually required. This is like the way learning slogans may precede a deeper commitment to a political ideology (p. 152).

From our own teaching experience we would argue that such "slogans" are a common component of the undergraduate learning experience in university science. Below we present examples of discourse imitation—instances where students are fluent in one or more modes of disciplinary discourse of the university physics community, but where they have apparently not experienced the corresponding facets of the way of knowing which the segment of discourse represents.

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 formula $\nabla\mathrm{x}\mathbf{E}=0$ which represents the mathematical operator, curl, of the electric field vector **E** being equal to zero]
Student: Um, I think the **E** is er the intensity of er an electric field. And then the curl of **E**… [quietly, under the breath] 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.

It is possible to convincingly argue from the above transcript that the student is discursively fluent in the mathematical and oral modes with respect to this particular way of knowing (the curl of the electric field for the electromagnetic case). Here one can see strong supporting evidence for diSessa's (1993) "learning slogans" in the words "conservative vector field". The student knows the expression and uses it appropriately, but it carries little, if any, holistic meaning or appresentation. It is clear that the student has not experienced the way of knowing this phrase represents. Here, the lecturer was using this idea to provide a conceptual link between the electrostatic case (magnetic field constant)—that he presumed was already well understood—and the case of the varying magnetic field that he intended exploring as his object of learning. In our terms this student's description exhibits discourse imitation. The student can calculate answers using the curl of **E** formulation (in fact this student had been one of the more successful participants on the degree course up to that point and self-reports finding the mathematics needed for physics easy), however, it is evident that in this case the student does not know what it is that has been calculated. This ability to use a mode of disciplinary discourse but not experience the way of knowing that it represents—in this case, to be able calculate, but not know what or why—is taken up by another student with respect to a parallel course.

> Student: [talking about tensors] 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].

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 disciplinary way of knowing that this mathematical mode represents is still not available to the student.

Translation between modes

From our data iterations we have suggested that discursive fluency in some of the representative modes of physics discourse may be insufficient to constitute an appropriate holistic experience of physics ways of knowing. For example, here is a student talking about learning quantum physics:

> Student: You can calculate using a mathematical formula in physics but you don't understand what's happening. You want to translate into plain Swedish—what's happening in physics through the math—but that's not always easy. Especially not now because now you can't really see a picture of it or understand really what it is that's happening in quantum physics.
> Interviewer: Mmm, that's interesting. Do you think there are some things that can only really be described with math in this subject?
> Student: Yeah, I think so.
> Interviewer: There aren't really adequate Swedish words to describe what's going on?
> Student: Yeah—and no English ones either. It's only math, only math can describe it properly. And just that—that there aren't really any words for this—gives you a feeling that it doesn't really exist—you can't really 'see' it—it doesn't really exist *you can only calculate it.*

We interpret this student's suggestion that only mathematics can describe quantum physics as further confirmation that different modes of disciplinary discourse play different roles in offering access to physics ways of knowing. Moreover, different disciplinary ways of knowing appear to be best represented through different combinations and "proportions" of modes. Certainly, as the student suggests, the disciplinary way of knowing which we call quantum physics is best represented through a higher "proportion" of mathematics in relation to oral and written language than say Newtonian mechanics. We suggest this student is struggling with the appresentation aspect and consequently is attempting to translate the meaning in the mathematical mode to some kind of meaning in the oral (line 2) and visual (line 4) modes. Following Stern, Aprea, & Ebner (2003) and Duval (2002; 2006) we believe that such re-representation of meaning is an important part of learning because such translation between modes offers the possibility of opening up further facets of a disciplinary way of knowing that a learner was previously unaware of, or unable to fruitfully access. This interpretation can be seen to be supported by the following dialogue taken from an interview with another student:

Student:	It's different for me to… maybe I think I understand and then I should calculate but then I cannot do it—so maybe I haven't understood er, maybe I just *think* I understand but I, I don't actually, because it's hard to calculate.

Here we argue that the student recognized that efforts to move from the written and oral modes of disciplinary discourse—reading about and listening to descriptions of a way of knowing—to the mathematical mode—"calculating"—revealed a "movement mismatch" between the modes of disciplinary discourse. Thus we suggest that students who have not appropriately experienced a disciplinary way of knowing may have the possibility for such an appropriate experience opened up for them by translation between modes. In this respect, Lemke (1998) claims that experienced scientists handle problems that would otherwise be impossible to solve by orchestrating movement between a wide range of semiotic resources—or, in our terms, translation between modes of disciplinary discourse:

> We can partly talk our way through a scientific event or problem in purely verbal conceptual terms, and then we can partly make sense of what is happening by combining our discourse with the drawing and interpretation of visual diagrams and graphs and other representations, and we can integrate both of these with mathematical formulas and algebraic derivations as well as quantitative calculations, and finally we can integrate all of these with actual experimental procedures and operations. In terms of which, on site and in the doing of the experiment, we can make sense directly through action and observation, later interpreted and represented in words, images, and formulas (p. 7).

Similarly, since each mode both has and opens up different possibilities for meaning-making, it therefore seems reasonable to argue, following Marton & Tsui (2004), that from a "variation needed for learning" point of view, a multimodal approach to teaching will enhance the possibility of appropriate learning. For example, here we have a student describing the usefulness of multimodality in her own learning:

Student:	I usually write down more or less everything the teacher writes on the board.
Interviewer:	Even though it's there in the book?
Student:	Yeah. At least with the theory..

I think it's more comfortable to write down derivations and so on—if you write it down it goes in another, one more way so to speak.
Interviewer: Aha, so the doing in some way…?
Student: —Yes, I think so.

We see this student's use of a multimodal approach as an example of Linder & Marshall's (2003) notion of purposeful repetition, that is we equate the student's movement, transfer and translation between modes with creating the opportunity to experience critical variation in the object of learning.

Critical constellations of modes

From the point of view of disciplinary discourse, we can say that no one mode in itself can ever be holistically representative of a disciplinary way of knowing, and therefore it is impossible to experience disciplinary ways of knowing through discursive fluency attained in one mode alone. That is not to say that monomodal discourse may not be useful within the scientific community—in fact just the opposite is true. Once students have discursive fluency across modes, the presentation of a few short phrases, a mathematical formula, or a simple diagram, functions as a sort of disciplinary shorthand that facilitates powerful meaning sharing. In other words, those facets of a way of knowing which are not present in the immediate representation are spontaneously appresent. For example, as we pointed out earlier, for the majority of students in the lesson with transformers the diagram that the lecturer drew on the board appresented something appropriate. Simply drawing the diagram evoked a whole dimension of shared meaning, much of which could open up the possibility of coming to know mutual inductance. One way of characterizing this is to draw on Wittgenstein's (1958) idea of students and lecturer playing the same language game. This kind of mutually accepted system can only occur if both student and lecturer have experienced the ways of knowing of some part of the discipline. As we have argued here, such ways of knowing may perhaps only be holistically experienced through certain types of disciplinary discourse.

What we are suggesting, then, is that each way of knowing in, for example, physics may only be constituted by a certain *critical constellation of modes*. Once a way of knowing has been holistically experienced, all or part of it could be activated across several other modes, but first one needs fluency in a particular, critical constellation of modes.

Naturally, we do not mean to suggest that providing students with access to a certain constellation of modes is sufficient in itself to guarantee a desired learning outcome—far from it. A great deal of research has pointed to the importance of other factors beyond difficulties that students have dealing with the semiotic resources that a discipline offers for the teaching, learning and other sharing of its ways of knowing. Here examples that need to be considered in descriptions of learning science include attributes such as gender and power relations (Conefrey, 1997; Seymour & Hewitt, 1997; Thomas, 1990), student epistemology (Hammer, 1995), culture (Brown, 2004), group dynamics (Bianchini, 1997), approaches to learning (Marton & Säljö, 1976; Svensson, 1976, 1977, 1984), etc. Thus, much of our illustrative interview data could be gainfully interpreted from any or all of these perspectives. What we are arguing for here is that, irrespective of these student-related factors, certain disciplinary ways of knowing may be impossible to appropriately constitute without discursive fluency in a critical combination of modes.

Discussion

Our characterization of student learning in university science in terms of disciplinary discourse has brought to the fore two ideas which we suggest have not been thoroughly explored in the literature: discursive fluency and discourse imitation, and one idea—critical constellations of modes—which we have not seen discussed elsewhere. We will now discuss each of these ideas in turn.

Discursive fluency: "discoursing" in university science

We have proposed that a person needs to become discursively fluent in a particular set of modes of disciplinary discourse before the possibility is opened for the facets of the way of knowing that are described by these modes can become accessible to them. However, the interview illustrations that we drew on for this article suggest that discursive fluency does not assuredly lead to one experiencing the related facets of a disciplinary way of knowing. We therefore proposed that discursive fluency is a necessary, but not sufficient condition for experiencing a disciplinary way of knowing.

From our multimodal viewpoint, simple exposure to disciplinary discourse is not enough for students to experience disciplinary ways of knowing; students need practice in using disciplinary discourse to make meaning for themselves. Givry & Roth (2006) have described how student meaning making with semiotic resources may not initially have a stable sense but can change over a short period of time, even within the same context. In this respect, Northedge (2002) has suggested that teachers ought to scaffold student meaning making. Students should be expected to initially make "fuzzy" meaning—that is their discourse will initially be a poor imitation of disciplinary discourse, but, with appropriate guidance, gradually this will spiral towards something closer to the discourse of the discipline (they achieve discursive fluency). We see examples of such scaffolding of multimodal student discourse in Stern, Aprea, & Ebner (2003) and Kozma, Chin, Russell, & Marx (2000). In our terms then, the role of the teacher should be one of guiding students away from the use of variable, context-dependent semiotic resources, to the use of the standard, disciplinary discourse for each disciplinary way of knowing within a given context. Hammer, Elby, Scherr & Redish (2005) can be seen to have arrived at a similar conclusion although from a quite different starting point. From our work with teachers and students and our own experience of university physics we feel that the supporting of students' own meaning making within disciplinary discourse is typically not a common practice in university science education. In university science education, such scaffolding of student use of disciplinary discourse appears to be limited to guidance in using the tools and carrying out the activities of science in laboratory work, along with some mathematical guidance in formal problem-solving sessions—although in the latter situation it is not uncommon that students are reduced to passive observers whilst the lecturer demonstrates the mathematical mode of disciplinary discourse.

Lemke (1990) believes that students should be given the chance to "talk science", whilst Tobias (1986) has suggested that learning would be enhanced if science students were encouraged to "kick the ideas around" as they typically are in the social sciences and humanities. From our perspective we reformulate these assertions by suggesting that students need to be given the opportunity in a supporting environment to "discourse" in science, in order to gain the necessary fluency. That is, students need opportunities to practice using a range of modes of disciplinary discourse with respect to the various objects of learning that their program is made up of. The students in our interviews repeatedly indicated that a large segment of their learning occurs when "discoursing" with each other using what we could recognize as being various modes of disciplinary discourse. This is similar to the findings of Svensson & Högfors (1988). Unfortunately, this "discoursing" occurs in *ad hoc* problem-solving study groups, rather than when interacting with university lecturers. We therefore suggest that the knowledge of the lecturer as a fluent user of disciplinary discourse is often under-exploited in university science. In our experience many science lecturers appear to at best reconstitute the representations, tools and activities of science in language terms, or at worst even take them for granted.

One way of thinking about this problem is to see science learning as metaphorically analogous to learning a foreign language. The easiest way to learn a foreign language is to travel to a country where the language is spoken and then stay there for a while, interacting with native speakers. Similarly, the easiest way to learn science is through *doing* science together with scientists. Following Northedge (2002) we propose the lecturer, as a person competent in disciplinary discourse, should rather act as a guide in this respect, not only modeling disciplinary discourse but also actively engaging students in their attempts to make meaning with such discourse for themselves. Ironically, at the moment this role seems to be filled by fellow students, who are themselves struggling to learn the discourse of the discipline.

Imitation-revelation

We have argued that students may use disciplinary discourse appropriately but still fail to holistically experience a disciplinary way of knowing. If such discourse imitation continues for any length of time without an experience of the corresponding facets of a disciplinary way of knowing, we argue that students may set out on an imitation-revelation learning trajectory. On this trajectory students may experience the disciplinary way of knowing in a sudden "Eureka!" moment or revelation. In such cases, the discourse in which a student has become fluent is suddenly and spontaneously linked to the disciplinary ways of knowing that it represents.

Although we have no data to directly exemplify this, Ahlberg (2004) documented cases where student interns first experienced something in their internship in one way and then came to experience it in another (the disciplinary) way. From our perspective we reinterpret these early student experiences as extreme instances of discourse imitation—that is students described situations where they had become fluent in disciplinary discourse (in this case participating in the day-to-day activities of a hospital) without experiencing the associated ways of knowing that this discourse represents. We suggest that usually, however, this linking of disciplinary discourse to facets of ways of knowing occurs in much smaller, less noticeable steps. Thus, although almost all the students in Ahlberg's study could identify one situation when they noticed such a change in their experience of a way of knowing, from our own teaching experience we would suggest that learners will, for the most part, find it difficult to point out precisely when discursive fluency has led to them to experience a particular disciplinary way of knowing.

Expecting discourse imitation

Part of our analysis brought to the fore the notion that the route to learning a disciplinary discourse involves at least some element of discourse imitation, that is students appear to initially achieve discursive fluency without holistically experiencing the associated disciplinary ways of knowing. If this is indeed the case, then lecturers need to be reflective about student learning not only when students show that their understanding is lacking in some aspect(s), but also when students seemingly do understand appropriately through the provision of "correct" answers. Lecturers need to be as sure as they can be that their students are playing the same "language game" (Wittgenstein, 1958) as the rest of the discipline. Wickman & Östman (2002) discuss how Wittgenstein's language games can be operationalized, using the idea of lingering gaps in discourse. An experienced and insightful lecturer, who has come to know students as learners will notice these gaps and see them as a cue for further efforts to promote holistic and appropriate understanding (Prosser & Trigwell, 1999).

Discourse imitation: a result of using a reduced set of modes?

It is now well established that assessment plays an important role in influencing what approach—deep or surface—that students adopt for parts of their learning (Fransson, 1977; Hakstian, 1971; Marton & Säljö, 1976; Newble & Jaeger, 1983; Peters, 1982; Scoulier & Prosser, 1994). If disciplinary ways of knowing may only be constituted through discursive fluency in a critical constellation of modes, then we suggest that the design of assessment which takes into account these modes will help shift students towards a deeper approach to learning (and hence minimize prolonged discourse imitation).

This in turn suggests what many in university science education argue, namely that the traditional method of examining science courses through problem-solving and calculation may lead to students passing examinations without appropriately experiencing the ways of knowing of the discipline. Furthermore, since disciplinary discourse is multimodal, examinations using mainly the mathematical mode may encourage prolonged discourse imitation (surface approach to learning), particularly at introductory levels. Why should a student pay attention to all those other modes if the perception is that only the mathematical mode is formally graded? For physics, the monomodal mathematics case was well critiqued by Hewitt (1983) in his 1982 Millikan Award Lecture as follows:

> Why is it common for students to avoid basic physics and instead take biology? Biology is much more complicated than physics. Physics is so simple, in fact, that it's easily expressed in mathematical form. But that's the problem for most people; because it *can* be expressed mathematically, *it is*. And for most people, mathematics is a foreign language. The reason more students elect biology is because it's common knowledge that biology is taught qualitatively while physics is taught quantitatively. *Physics is easy to teach mathematically, but we make a mistake by then assuming it is easy to learn mathematically* (p. 305, emphasis added).

Today, over a quarter of a century later, the physics education research community has hardly progressed at all from this position. The extensive work carried out in higher education, has principally been centered on difficulties that students have in learning through certain semiotic resources (see Redish, 2003 for an excellent collation of this work). Research which explores the ramifications and possibilities for enhancing learning by combining semiotic resources in "the variation approach to learning" (c.f. Marton & Booth 1997; Marton & Tsui 2004) is almost unheard of (in fact the only example we could find was Linder, Fraser, & Pang, 2006).

Critical constellations of modes

We have proposed that learning how to appropriately represent the ways of knowing that constitute a discipline requires a wide range of modes, with each discipline (see discussion below) and each individual way of knowing within that discipline requiring differing proportions of these modes. Moreover, by referring to the phenomenological concept of appresentation, we further proposed that in order for students to have the possibility to fully experience disciplinary ways of knowing they need to become discursively fluent in a critical combination of modes of disciplinary discourse. Building on the proposal and its illustrations that we have so far given we have argued for two important contributions to a "pedagogy of learning" (Lo, Marton, Pang, & Pong, 2004). Firstly, that multimodal teaching has the distinct potential to lead to better and more comprehensive learning outcomes than teaching with a reduced number of modes. Secondly, that it then becomes of utmost importance that research be carried out into *which* constellation of modes best opens up the possibility for experiencing each of the particular ways of knowing of physics.

Critical constellations of modes in other disciplines

Clearly the proportions and combinations of modes are radically different when we examine ways of knowing in disciplines other than university science. As we pointed out in the introduction to this article, we have built on Fairclough's (1995) ideas to suggest that each discipline has its own specific order of discourse or disciplinary "grammar". So, whilst there may only be a limited number of modes that contribute to discursive fluency in a discipline, each discipline uses and develops the "grammar" of these modes differently. For example, art history would use very different modes than economics. We could expect art history to have a much more developed use of the visual mode, using a much more complex visual grammar or order of discourse for that particular mode than economics. Even when disciplines appear to use a mode in similar ways this can be misleading. For an example, suppose political science students and physics students were independently asked to interpret the following statement: "The work done by a conservative force is zero". Although both sets of students receive the same input in exactly the same mode, we would argue that political science students would relate this to a way of knowing centered around liberal/conservative political rhetoric, whilst physics students would relate this to the work on an object by a force being independent of the path taken by the object. The meanings carried by the components "work done" and "conservative force" would have nothing in common beyond their superficial word-sounds.

Do more modes mean the discipline is more complex?

Disciplinary ways of knowing can be more or less complex and/or more or less abstract. In general, the more modes a discipline uses, the higher the complexity and abstraction of the disciplinary way of knowing they describe. It is tempting to suggest that a discipline like physics which uses a wide variety of modes is more complex than say English literature which uses much fewer modes. However, as we posited earlier, disciplines develop their orders of discourse in different ways. To say that English literature is less complex than physics since it uses fewer modes would be to overlook the specialised growth in the use of oral and written modes that has occurred in the discipline of English literature. In this respect physics discourse could be viewed as only functioning at a very basic level within these oral and written modes. So, a more complex learning task would require either more modes for appropriate constitution or a more highly developed use of a few modes (more complex order of discourse). However, if a discipline does have a large number of modes, then students will need to become fluent in all of them. Moreover, following Lemke (1998), students will need to "orchestrate movement" (p.7) between these modes in order to more fully represent a disciplinary way of knowing. Thus, it *could* be argued that the more modes, the more difficult it is to become discursively fluent in that discipline—simply because students might not see the need to develop the full complement of modes and hence be satisfied with fluency in a reduced set.

Summary & pedagogical implications

We have made a proposal using empirical illustrations that a fruitful way of characterizing learning in the context of university science education, such as physics, is in terms of becoming fluent in a system of semiotic resources, which we characterize in terms of modes of disciplinary discourse—those parts that make up the complex of representations, tools and activities of a discipline. This proposal draws on the work of others and then, in the context of university science education such as physics extends the idea into an area we have not seen discussed before: that fluency in a critical constellation of modes of disciplinary discourse is necessary (though not always sufficient) for opening up the possibility of appropriate holistic learning i.e., gaining meaningful access to disciplinary ways of knowing. Thus the proposal presented in this article represents the first steps towards characterizing student learning in university science from a discourse perspective. This leads us to bring together our discussion by unpacking the following pedagogical questions:

1. What are the essential aspects that a lecturer would need to give consideration to when viewing the learning experience of the disciplinary discourse of university science in a subject such as physics?
2. How could a lecturer expect the learning of disciplinary discourse to relate to the students' experience of disciplinary ways of knowing?
3. What are the implications of the disciplinary discourse approach for the organization of university science learning?
4. How could a lecturer start to tease out the necessary critical constellation of modes of disciplinary discourse for a given object of learning?

With respect to the first question of how students characterize their learning of the disciplinary discourse, we have argued that:

- *The disciplinary discourse of university science is of necessity multimodal.*
- *A repetitive, practice element is a necessary part of learning university science.*
- *This repetitive practice is the means by which students become fluent in disciplinary discourse.*

With respect to the second question regarding the way in which learning a disciplinary discourse relates to students' experience of the disciplinary ways of knowing, we argued that:

- *Discursive fluency in a particular mode is a necessary but not sufficient condition for experiencing the facets of a disciplinary way of knowing that that mode allows access to.*
- *An element of discourse imitation may be a natural stage on the way to experiencing a disciplinary way of knowing.*
- *Translation between modes can help students notice discrepancies between their way of knowing and that of the discipline.*
- *Only certain critical constellations of modes of disciplinary discourse may be able to afford access to disciplinary ways of knowing.*

When it comes to the third question about the consequences for the organization of university science, our proposal presents a number of ideas that have already been suggested by others. What is new here is the epistemology that a teacher adopting our approach would employ to justify these already accepted teaching strategies.

- *Students need opportunities to practice using the representations, tools and activities of the discipline as an integral part of their science education.*
- *The assessment criteria for university science courses should reflect the multimodal nature of disciplinary knowledge, i.e. assessment should be authentic.*
- *The specialist knowledge of lecturers as experts in using disciplinary discourse may often be under-exploited in university science lectures.*

Our fourth question asks how a lecturer could start to tease out the necessary critical constellation of modes of disciplinary discourse for a given object of learning. Here we suggest:

- *To improve the possibilities for learning, lecturers need to come to better understand the specific constellations of modes necessary for a full representation of each individual disciplinary way of knowing.*

We argue that if university science lecturers do not come to a better appreciation of which modes are necessary for an appropriate holistic experience of a disciplinary way of knowing; it will be difficult to adequately constitute learning experiences which provide the necessary variation in critical constellations of modes of disciplinary discourse.

Many objects of learning in, say physics can be teacher-thought-about in terms of the following modes: oral (words), visual (sketches diagrams and graphs), activities (practical work), tools (apparatus) and mathematics (equations, derivations, formulae and fundamental theorems) and ways to relate and translate between these modes. Giving a full example here would be complex and undesirably long, so as a straightforward kind of illustration, since we discussed this briefly earlier, consider the teaching of Ohm's law. In oral mode a physics lecturer could think about ways of representing how the total current flowing from one electrode to another is proportional to the potential difference between them. In visual mode this lecturer could consider circuit diagrams that require predictions about relative bulb brightness of series and parallel battery-bulb configurations. These predictions could then be tested in the active mode in the laboratory. Here too ammeters and voltmeters can be used (tools mode), and a series of readings can be used to create tables and graphs (visual mode). In the mathematical mode a lecturer could consider deriving Ohm's law through an exploration of relations between electromagnetic force, current density, force per unit charge, conductivity, resistivity, electric field, the drift velocity of charge, and magnetic field in order to obtain a mathematical expression that represents current density as being proportional to the force exerted per unit charge (proportionality factor being seen in terms of either conductivity or as resistivity).

Conclusion

Much of the research carried out in university science education focuses on new ways of understanding old problems. Our study suggests that viewing learning in terms of disciplinary discourse with an emphasis on practice in order to achieve discursive fluency in a critical constellation of modes, opens up another useful dimension in the modeling of learning in university science which is potentially very fruitful for teachers and students alike.

Author Note

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