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CHAPTER 7

MULTIMODAL KNOWLEDGE: USING LANGUAGE, MATHEMATICS AND IMAGES IN PHYSICS

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INTRODUCTION

What knowledge do students need in order to be successful in science? Such a question pushes at the heart of educational programmes that aim to develop a comprehensive pedagogy that reaches across disciplines. In one sense, the answer is simple. The knowledge students need is specified in the syllabus, detailed in the textbook and explained in the classroom. From this perspective it is simply a matter of reading the textbook, listening to the teacher and writing down the knowledge in the exam or in an assignment. However, few in educational research would argue for such a simplistic model. For one, it is clear from decades of research into literacy across the curriculum that the processes of reading, listening and writing are far from unproblematic. From an educational linguistic perspective, there is a range of highly specific literacies at stake; students must be able to read and write a wide range of scientific genres, and interpret and make use of highly intricate scientific language (Martin 1985, Lemke 1990, Rose et al. 1992, Halliday and Martin 1993, Christie and Martin 1997, Martin and Veel 1998, Unsworth 1997, 2001a, Halliday 2004, Martin and Rose 2008, Martin and Doran 2015, Hao 2020). In the classroom they need to be able to listen and interpret what the teacher is saying, engage with them in dialogue and successfully reconstrue scientific meanings at the teacher's bidding. (Rose 2004, 2014, 2020, chapter 11 of this volume, Christie 2002, Rose and Martin 2012). These literacy demands involve not just language, but extend to the multiliteracies inherent in science schooling – where language, mathematics, images, specialized symbolic formulae, animations, and demonstration apparatus all need to be 'read' as one and reorganized where necessary in assignments and exams (Lemke 1998, 2003, Kress et al. 2001, Unsworth 2001b, O'Halloran 2005, Parodi 2012, Doran 2017, 2018, 2019, Doran and Martin, chapter 5 of this volume). To learn the knowledge of a discipline, one must be able to grasp the way it is construed through language and other semiosis; and to show you have the knowledge, you must be able to marshal these specialized linguistic and semiotic resources to reconstrue these meanings.

Such mastery of a wide range of literacy demands is in many ways the crux of many issues in learning how to do science. But simply being able to read and write scientific language and the particular text types needed across the curriculum is not enough. Students need to understand where and when each particular text type, semiotic resource or particular linguistic resource is appropriate. They need to be able to interpret new situations and new demands and organize the meanings they have learnt in an appropriate manner. That is, they need to understand the principles underpinning the selection and application of particular meanings and why they are used. At stake here is a way of seeing the world. Students must develop a scientific gaze that allows them, amongst other things, to shift between the knowledge of the empirical world and that of abstract theory, and between everyday understandings and technical conceptions. They need to be able to make connections between phenomena that at first glance may seem disparate and carry out specialized procedures and protocols to investigate prescribed phenomena. And they must be able to marshal particular literacies to do this at the appropriate time.

This chapter explores how knowledge is organized multimodally in science, focusing in particular on physics as it is taught in schooling. It will explore two main concerns: the technical meanings construed through the key resources of language, image and mathematics, and the underlying principles that organize a scientific gaze and enable students to understand when to use particular technical meanings and semiotic resources. To do this, it will view the meanings made from two perspectives. First it will consider scientific meanings through the register variable *field* from Systemic Functional Linguistics (SFL) (Doran and Martin, chapter 5 of this volume). Second it will explore these meanings through the sociological framework of Legitimation Code Theory (LCT), which is being widely used alongside SFL (Maton and Doran 2017a, Martin *et al*. 2020), specifically its dimension of Semantics (Maton 2014, 2020).

The perspective from field in SFL will explore how particular technical meanings are organized by different resources – language, mathematics and image. Here we will be concerned with whether technical meanings are presented *statically* as set of items positioned in taxonomies (either of classification – type/subtype, or of composition – part/whole), or whether they are presented *dynamically* as series of events (known as activities) given in more or less detail. In addition, we will be concerned with whether these items or activities involve particular properties that can be measured and to what degree all of these meanings are placed in large, interdependent networks of meaning. Each dimension of field will be introduced in more detail as they become relevant, but this analysis will show that particular semiotic resources tend to specialize in particular ways of organizing meaning, while backgrounding others. In this sense, this chapter will show that the organization of content in many disciplines is inherently multimodal, as particular components of its technical array tend to be given full expression through particular semiotic resources.

Complementing this view from SFL we will also consider knowledge in physics from the perspective of Semantics in LCT (Maton 2014, 2020). This will give an insight into two organizing principles that characterize knowledge practices. The first is known as *semantic gravity* (SG), which conceptualizes the degree of context-dependence of meaning. Stronger semantic gravity (SG+) indicates meanings are more dependent on their context; weaker semantic gravity (SG–) indicates meanings are less dependent on their context. For example, in a primary school physics text that we return to below, the concepts of pushing and pulling are introduced by listing a series of examples, such as *Michael pushes the keys to a tune*, which refers to an image of a child playing a keyboard (Riley 2001). In this case, we would say that the *pushes* here involves relatively strong semantic gravity (SG+) as it is dependent on a particular instance of pushing – it has relatively high context-dependence. In contrast, later on in the book, the text generalizes in order to introduce the concept of *force*, using the sentence *A push is a force*. Here *push* does not make reference to any particular instance of pushing, rather can be applied to any number of instances. In this case, we can describe *push* as indicating weaker semantic gravity (SG–) than the first instance as it has less context-dependence. Shifts in semantic gravity are crucial to the organization of knowledge in physics (and indeed all sciences), and are organized through language, mathematics and image.

The second organizing principle at the centre of Semantics in LCT is *semantic density* (SD). Semantic density refers to the complexity of meaning. Stronger semantic density (SD+) indicates more complex meanings; weaker semantic density (SD–) indicates less complexity. In the sentence *a push is a force,* the term *force* is a technical term in physics. As students move through the years, this term becomes more centrally integrated into the vast network of meaning organizing physics knowledge. For example, it underpins Newtown's laws of motion, which organize the field of mechanics; it underpins different types of field in both nuclear physics and in relativity; and it forms a variable within innumerable mathematical equations at all levels. In this sense, *force* exhibits relatively strong semantic density (SD+) as it has a relatively complex set of meanings associated with it. In contrast the term *push* exhibits significantly weaker semantic density (SD–), as it does not resonate out to the same degree range of technical meaning in the field.[i]

Semantic gravity and semantic density can vary independently. On this basis, the *semantic plane* in Figure 7.1 (Maton 2016: 16) shows the possibilities for variation – with semantic gravity and semantic density as axes and each quadrant representing a different *semantic code*.

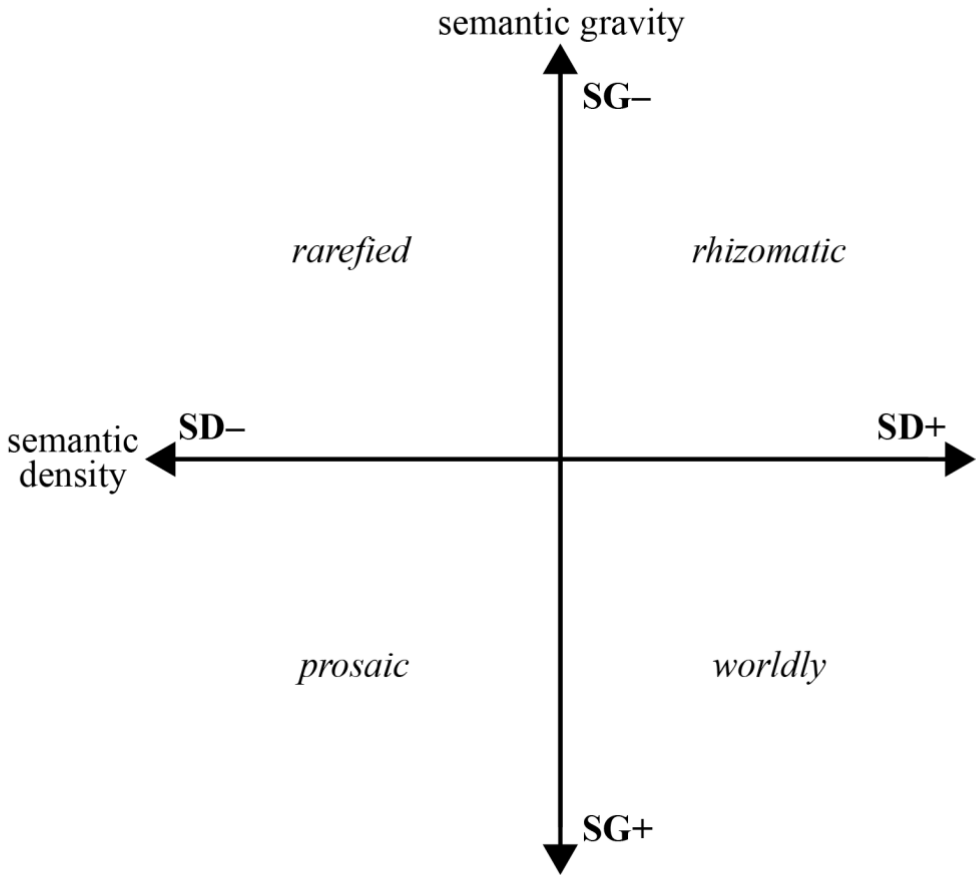


Figure 7.1. The semantic plane (Maton, 2016, p. 16)

Rhizomatic codes (top-right quadrant) indicate meanings that maintain weaker semantic gravity (SG–) and stronger semantic density (SD+). In common-sense terms, this quadrant indicates meanings that are relatively 'generalized' and 'complex', as often exemplified by technical theory. In contrast, *prosaic codes* (bottom-left quadrant) indicate meanings that are stronger semantic gravity (SG+) and weaker semantic density (SD–); meanings that are 'concrete' and 'simple', and often illustrated with common-sense everyday knowledge. *Worldly codes* (bottom-right quadrant) indicates stronger semantic gravity and stronger semantic density; meanings that are both highly context-dependent and very complex. This quadrant is often illustrated by knowledge in areas such as vocational education, and practically oriented fields and crafts, where projects are often embedded in a specific instance or case (such as building a particular bridge over a particular river) but involve a complex knowledge-base to achieve their goals. Finally, *rarefied codes* (top-left quadrant) indicates meanings with weaker semantic gravity and weaker semantic density; meanings that are relatively context independent but simple.

The *semantic plane* enables us to see the possible combinations and gradations available across the disciplinary map. Focusing on physics, it is tempting to immediately position it within the top-right quadrant as a *rhizomatic code* – as being both 'abstract' (weaker semantic gravity) and 'technical' (stronger semantic density). Indeed if we follow Biglan's (1973) characterization of physics as a relatively 'pure' discipline (i.e. non-applied) and a relatively 'hard' science, or Kolb's (1981) description of physics as both a relatively reflective (non-applied) but also a particularly 'abstract' discipline, then a classification of physics as a rhizomatic code makes sense. However, once we look at the actual practices of any field, it becomes clear very quickly that no discipline fits into a single box. There is immense variation across sub-disciplines (is it nuclear physics? classical mechanics? electromagnetism? astrophysics?); across year level (elementary, secondary, tertiary? which year in each?), across individual classes and across research, practice and education. LCT is invaluable here: the semantic codes are not boxes – the semantic plane is a topological space with indefinite variation *within* each code.

As we will see, one of the key shifts that occurs in physics texts from secondary education onwards is the ability to move between abstract theory and empirical instances while still using highly complex knowledge. Put another way, a key pattern is the varying of semantic gravity while maintaining relatively strong semantic density – shifts between rhizomatic codes and worldly codes. Similarly, when teaching new concepts, teachers and textbooks will regularly shift between 'everyday', 'concrete' knowledge of examples (prosaic codes) and the abstract theoretical knowledge typically considered the realm of physics (rhizomatic codes). In short, the key to doing physics is not just in being able to understand highly technical, abstract knowledge, but to vary the abstraction and technicality as required by the situation and to utilize the particular semiotic resources that organize this.

The following sections will step through the ways language, mathematics and image are used to organize both the technical meanings of physics and the shifts in semantic gravity and semantic density that allow students to bridge between 'theory' and the 'everyday', the 'empirical' and the 'abstract', and the 'concrete' and the 'complex'. First, it will focus on the developments in language that move knowledge from common-sense to technical understandings. Then it will turn to the move from language to mathematics in early secondary school and the reorganization of knowledge this entails. Finally, we will consider how the range of images used in physics complement the technical meanings and shifts in

Semantics seen in mathematics. In sum, we will see that the three semiotic resources work together to organize the knowledge of physics in a way that allows students to build a scientific gaze.

KNOWLEDGE THROUGH LANGUAGE

Language and activity

An early stepping stone into physics is exemplified by a book for elementary (primary) school students, focusing on pushing and pulling (Riley 2001). This book gives a series of examples of pushing and pulling with very large photos of each action:

> *When do you push?*
>
> > *You push a pram*
> >
> > *You push a swing*
>
> *When do you pull?*
>
> > *You pull a brush through your hair*
> >
> > *You pull a book from your bag.*

This very concrete set of examples illustrates a series of physical events. In terms of the SFL register variable field, these events construe *activities* (see Doran and Martin, chapter 5 this volume). Activities such as these offer the child a dynamic perspective on the world as happenings. To build a picture of the activities involving pushing and pulling, the text lists a long series of examples with large pictures of each activity:

> *A digger pushes rocks into a heap.*
>
> *A toy car needs a push to make it go.*
>
> *Michael pushes the keys to play a tune.* [referring to playing the keyboard]
>
> *Alex pushes the ball when he kicks it.*
>
> …
>
> *An engine pulls a train.*
>
> *A tractor pulls a trailer.*
>
> *A dog pulls on its lead.*
>
> *Tim pulls on a jumper*.

From the perspective of more advanced physics, this listing of examples appears relatively simple. However it performs a crucial early role in building an uncommon-sense understanding of the world. By listing a series of other quite different activities (kicking, playing with a car, piling rocks in a heap, putting on a jumper, driving a train) as 'pushing' and 'pulling', the text emphasizes their similarity and categorizes them as instances of the more general activity of pushing and pulling. In addition, the book illustrates that a wide range of *items* may do the pushing or pulling or be pushed or pulled. This is an important move into scientific knowledge as it means first that all examples may be discussed along similar lines, and second that pushes and pulls can be found almost everywhere. The student is learning that this wide range of activities, in some sense, all do the same thing.

In terms of LCT Semantics, this weakens the semantic gravity of knowledge. The individual examples describe specific events that are relatively context-dependent. But as more examples are listed, the differences between them are generalized in a way that emphasizes their similarities as pushes and pulls. That is, the text weakens semantic gravity so that it can eventually discuss pushes and pulls as events of their own (discussed below). Similarly, in terms of semantic density, by listing this series of examples as *pushes and pulls*, it relates these otherwise distinct events together. This adds connections between their meanings, slightly adding to their complexity, and thus strengthening their semantic density. Although these are relatively small shifts in semantic gravity and semantic density in comparison to higher level physics, they are important first steps in learning this knowledge which will repeated regularly as students move through school.

Looking further into the text, we see it also illustrates that pushing and pulling has effects on the world ('^' indicates that one activity follows or is entailed by the other):

> *You push on clay to squash it flat.*
>
> > *You push on clay*
> >
> > ^ (in order to)
> >
> > *squash it flat*
>
> …
>
> *You pull an elastic band to stretch it.*

You pull an elastic band

^ (in order to)

stretch it

…

Paul pushes the pedals on his bicycle. The wheels turn round.

Paul pushes the pedals on his bicycle

^

The wheels turn round.

Here, the text presents *squashing*, *stretching* and *turning* as resulting from the pushing or pulling in the previous clause. Series of events such as these where one activity implicates or results from another are a key feature of scientific discourse (Wignell *et al*. 1993). From the perspective of field, they show chains of activity that are implicated by one another.[ii] Although at this stage each implication relation includes only two activities, later on in schooling these series become long and intricate, involving a range of possible dimensions of conditionality and causation (Rose 1998) and underpinning key genres in science such as explanations (Unsworth 1997, Martin and Rose 2008). Interpreting this from the perspective of LCT Semantics once more, these implication relations work to connect activities together, further strengthening their semantic density.

Activities and items

By generalizing a range of common-sense activities as ‘pushing’ and ‘pulling’, and linking them up with other activities to form series of implication activities, this primary school book has already taken some key steps in the development of an uncommon-sense scientific field. But the book does not stop here. After introducing a number of examples, the text nominalizes the activities of pushing and pulling as *pushes* and *pulls*, through a resource known as ‘grammatical metaphor’ (Halliday 1998):

> *A toy car needs a push to make it go*
>
> …
>
> *What pushes and pulls can you find as you play?*
>
> …
>
> *Can you think of three more pulls?*
>
> …
>
> *Emma gives a weak push to her car.*
>
> *Ben gives a strong push to his car.*

In doing so, the text reconstrues the activity of *pushing* and *pulling* as an item *push* and *pull;* it turns an ‘event’ into a ‘thing’. This is arguably one of the most significant moves in the transition to uncommon-sense knowledge (Halliday and Martin 1993, Halliday 1998), as it enables much greater possibilities for meaning than if it were dealing with *just* an activity, or *just* an item.

In this first instance, itemizing these activities enables them to ‘do’ other activities themselves. For example:

A push can squash something

…

A pull can stretch something

Here, the push and pull has been abstracted from any particular thing doing the pushing and pulling. This establishes a more generalized series of activities whereby one activity (the *push* or *pull*) leads to another (*squashing* or *stretching*). This further weakens semantic gravity, as the pushes and pulls are no longer tied to any particular instances:

Push

^

squash something

and

Pull

^

stretch something

This text does not take the next step of also generalizing the squashing and stretching and putting the whole series of implication in one clause, such as in *squashes are caused by pushes* (a specific type of grammatical metaphor known as a logical metaphor; Hao 2018, Halliday 1998). But through this initial grammatical metaphor, the book establishes the basic building blocks that students need for a scientific construal of experience.

Second, by itemizing *pushing* and *pulling* as *push* and *pull*, the text enables them to enter into relations normally reserved for items. This is most clearly seen toward the end of the book, when it specifies that:

> *A push is a force*
>
> …
>
> *A pull is a force*

Here, the pushes and pulls are classified as types of *force*. In doing so, the book establishes a *classification taxonomy*. As a wide range of previous events have already been described as pushes and pulls, this means they are all in turn classified as types of *force*. The term *force* then resonates out to a wide range of common-sense experiences into a single technical term (Wignell *et al.* 1993). Again in terms of LCT Semantics, this strengthens its semantic density, establishing a relatively large series of interconnections emanating from the technical term *force* (see Maton and Doran 2017b). As students move through later years of school, *force* will become increasingly central to the field of physics as it distils more and more meaning.

Language and properties

There is one final step this text takes in construing its scientific view of the world. This can be seen in the following example where the text notes that pushes and pulls can be stronger or weaker:

> *Emma gives <u>a weak push</u> to her car.*
>
> *Ben gives <u>a strong push</u> to his car.*

Ben's car goes further than Emma's car.

In the terms of Doran and Martin (chapter 5 of this volume) model of field, *weak* and *strong* are *properties* of the pushes. Properties are meanings attached to an item or an activity that can be graded as more or less. As this instance shows, by attributing the property of strength to the activities, the two pushes can be ordered as more or less strong (or *strong* and *weak*) – what is referred to as an *array* of strength (Doran 2018). Importantly, this array of strengths can also have effects. In this case, the differences in strength lead to a difference in the distance each of the cars go. One array, the strength of the push, leads to another array, the distance of the movement, shown by *Ben's car goes further than Emma's car*.

This potential for giving items and activities a property, ordering these properties into arrays, and setting up chains of dependencies and causation between different arrays, opens a further avenue for building connections between meanings and strengthening semantic density.

Building the scientific gaze

Although at first glance the meanings being made at this level may appear relatively simple, this text has introduced each of the main basic building blocks that students will need throughout their scientific study. From the perspective of field, the text has explored a *dynamic* perspective on phenomena as activities of pushing and pulling, complemented with a *static* perspective of pushes and pulls as items, and added gradable properties of strength to the pushes and pulls. In addition, the text has introduced small sets of relations between each of these meanings. It has brought together activities into relations of *implication*, where one activity entails another (such as *pushing* leading to *squashing*); it has brought together items into a small *classification taxonomy* whereby one set of items are positioned as types of another (i.e. *pushes* and *pulls* as types of *force*); and it has ordered sets of properties in relation to each other along an *array* (where *pushes* and *pulls* are ordered as more or less *strong*). Table 7.1 synthesizes the field-specific meanings made through language to this point.

Elements of field		**Examples**
activity	single activity	*An engine pulls a train.*
	momented as an implication activity	*You push on clay to squash it flat.*
item	single item	*What pushes can you find as you play?*
	items in a (classification) taxonomy	*A push is a force*
property	single property	*Emma gives a weak push to her car.*
	properties ordered into an array	*Ben's car goes further than Emma's car.*

Table 7.1. Elements of field in a primary school text

These elements of field underpin the content knowledge developed in science from primary school onward. As students move through schooling, implication series, uncommon-sense taxonomies and arrays will be extended and integrated; and as we will see in the following sections, they will be greatly elaborated through the use of images and mathematics. However, the introduction of these meanings do more than simply lay out the specific types of technical meaning needed in science. They also provide early steps in shifts that underpin the scientific gaze. In particular, they show a pathway through which students can move from relatively everyday concrete meanings to more uncommon-sense meanings. More technically in terms of LCT, they model a pathway from relatively weak semantic density to slightly stronger semantic density by raising the complexity of meanings, and from relatively strong semantic gravity to slightly weaker semantic gravity by lessening the context-dependence of meanings.

In terms of semantic density, we have seen that the text establishes relations between examples first by likening them together as examples of pushing and pulling, and second by connecting them into classification taxonomies, arrays, and relations of implication. This takes relatively distinct common-sense meanings and begins to establish a more elaborated networks of meaning. The final step in strengthening semantic density in this text comes through the introduction of the term *force*. By classifying pushes and pulls as forces, the text condenses all of the meanings established through the book into a single term. This positions it as a key instance of technicality in the field of physics (Halliday and Martin 1993), which exhibits relatively strong semantic density (Maton and Doran 2017b). Although the field of physics at this stage is not particularly elaborated, the term *force* is the first to position the entire discussion within the technical domain of physics.

At the same time, the text weakens the semantic gravity of its knowledge. It generalizes a series of distinct examples as the ‘same’ events – pushing and pulling – thereby moving them further away from any particular instance. It then reconstrues these events of pushing and pulling as items: *pushes* and *pulls*. This has the effect of extricating *pushes* and *pulls* from any particular things doing the pushing and pulling, and ensures they can be discussed as items in themselves. Extending this, by technicalizing *pushes* and *pulls* as *forces*, the text further lessens its context-dependence, weakening semantic gravity. As Doran and Maton (2020) argue, positioning meanings within more elaborated networks of meaning within a particular field tends to stabilize them. It makes them more dependent on other meanings in the field than on any particular context in which it is used, and in doing so weakens its semantic gravity.

These movements in semantic gravity and semantic density are mapped in Figure 7.2. As the plane indicates, a number of the linguistic resources used have effects on both semantic gravity and semantic density. This means that for students reading this text, the scientific knowledge to be learned is two-fold. On the one hand, students are to learn the specific content meanings associated with pushing, pulling and force – considered here through the field relations organizing scientific meanings. On the other hand, underpinning this, students are to learn that scientific knowledge involves reconstruing everyday situations into less context-dependent and more complex meanings that can resonate out to a range of other situations. In terms of LCT, they are learning that the scientific gaze involves being able to weaken semantic gravity and strengthen semantic density across a range of situations.

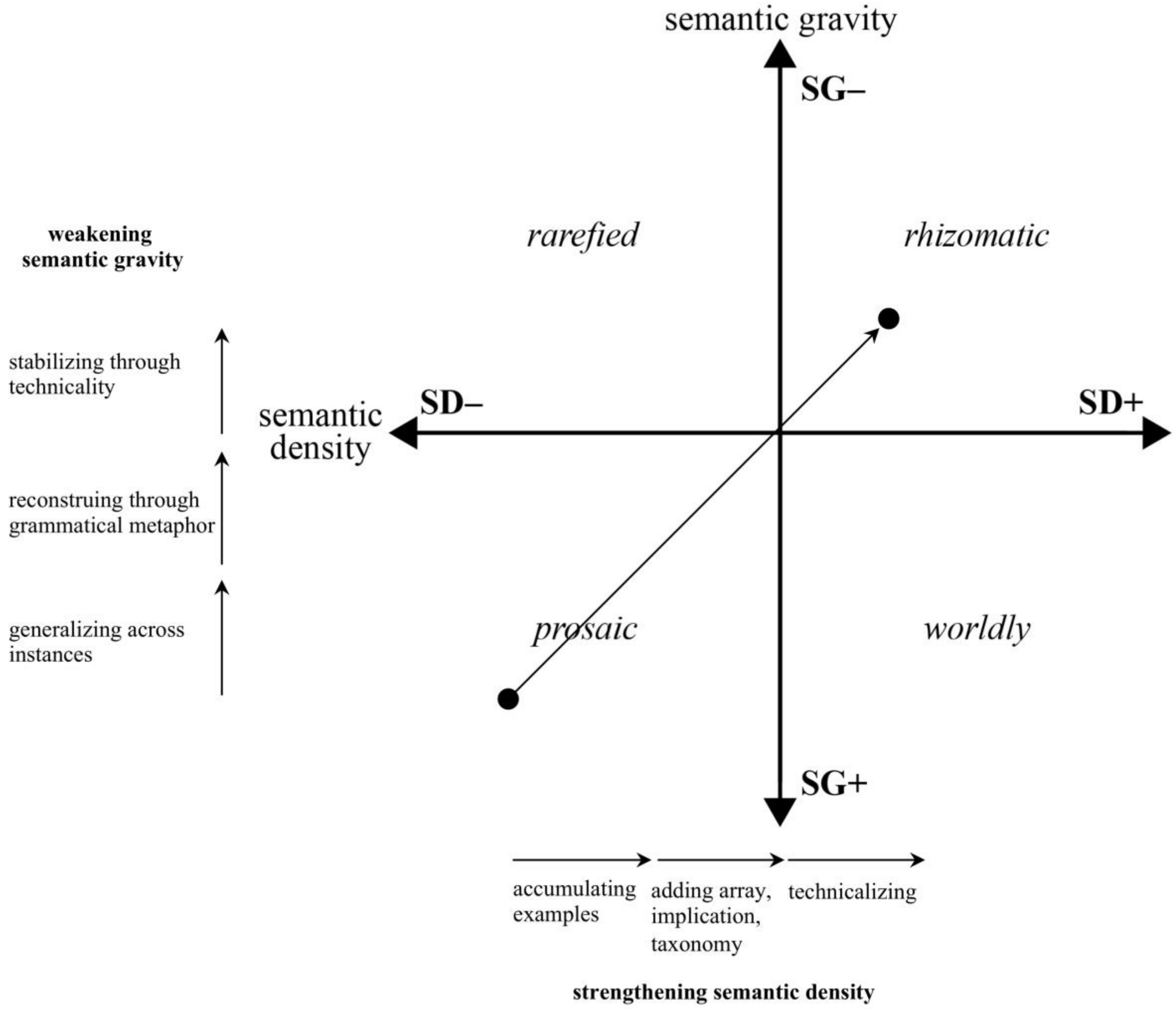


Figure 7.2. Movements in the semantic plane through the language of pushing and pulling

KNOWLEDGE THROUGH MATHEMATICS

Language occurs across all levels of science. The patterns shown in primary school where common-sense meanings are reconceptualized into uncommon-sense, technical meanings recur innumerable times throughout schooling. With each passing year, the expanse of these meanings increase, with deeper and more integrated relations in field being built, significantly strengthening semantic density. All the while, everyday meanings with stronger semantic gravity are reconceptualized in terms of more generalized meanings with weaker semantic gravity. For students successful in accessing the knowledge of science, this pattern instils a gaze that values movements from prosaic code (SG+, SD–) conceptions of the world to rhizomatic code (SG–, SD+) reconstruals.

From the perspective of activity, the later years of schooling build much longer implication series in order to explain and predict phenomena. These are complemented by activities associated with experimental procedures and recounts, which involve expectancy series. In these activities, relations tend to unfold through time in terms of what is expected to happen, rather than via definite entailment (Hao 2020, Doran 2018). In terms of taxonomy, larger classification taxonomies are complemented by compositional taxonomies that construe parts to wholes (such as a nucleus to an atom).

In addition to this, one of the major changes in the move from primary school to secondary school tends is often an increased emphasis on properties. As mentioned above, properties construe gradable phenomena – as in *the strength of a push*. These properties may be ordered into arrays – as in *one push is stronger than another*. Such arrays enable science to construe the world not just in terms of categorical distinctions, but also as involving infinitely variable gradations of more or less. This allows science to technicalize the 'fuzziness' of the physical world, where things are often distinguished by degree rather than in terms of discrete oppositions.

From secondary school onwards, a regular resource for organizing properties is mathematical symbolism (Doran 2017). Each symbol in a mathematical statement realizes a property.[iii] For example the equation $V = IR$ describes properties of electricity going through a conductor (known as Ohm’s law). This equation involves symbols where there may be more or less voltage (*V*), more or less current (*I*) or more or less resistance (*R*). The equation thus construes variation that occurs in the world.

Importantly, placing these symbols into an equation indicates that these properties are not independent. For any particular instance, not every possible value is available for each symbol. Rather, the equation specifies a set of relationships between each of these symbols whereby if there is a change in the value of one symbol, it will likely affect all the others. For example in $V = IR$, if I (the current) was to increase, then either V (voltage) would also need to increase, or R (resistance) would need to decrease, or both. Similarly, if V were to increase, then either I or R or both would also need to increase; and if R were to increase then either V would increase or I decrease or both (see Doran 2018: 88–96). As far as field is concerned, Doran and Martin (chapter 5, this volume) term these relations between properties *interdependency relations*. These interdependencies greatly expand the meaning potential of science. In the first instance, by involving properties, they allow scientific fields to construe degrees of gradation in ways that activity and taxonomy cannot. Secondly, by specifying definite interdependencies between these properties, they offer a means for describing the effects of a change in any particular property. Put another way, through the equation $V = IR$, physics is able to account for there being more or less voltage, more or less current and more or less resistance, and it is also able to precisely describe the effect of a change in voltage on the current or resistance of a conductor. By virtue of establishing interconnections between properties, mathematics also contributes to strengthening the semantic density of knowledge.

Mathematical equations can be organized into two key genres that deal with different aspects of scientific knowledge. These genres are known as *derivations*, which develop new relations between symbols, and *quantifications* which work to quantify symbols (Doran 2017, 2018).

Derivations are concerned with deriving new equations from previously known ones. In New South Wales, Australia, they tend to appear in physics in the later years of secondary school. For example in the following derivation from a secondary school student exam response, the student derives a new equation for *W* (*work*) (crudely, the energy associated with a force) in response to a question asking about the work needed to move a satellite from earth to an orbit altitude. Note that in the final equation, the *W* on the left side of the = is elided by convention in mathematical texts (Doran 2018: 69-72):

$$work = \Delta GPE = GPE_f - GPE_i$$

$$\therefore W = -\frac{Gm_1m_2}{r_f} - \left(-\frac{Gm_1m_2}{r_i}\right)$$

$$= Gm_1m_2\left(\frac{1}{r_i} - \frac{1}{r_f}\right)$$

The student begins by stating an equation that is assumed at this level, namely that *work* is equal to the change in gravitational potential energy (ΔGPE, meaning roughly the change in energy associated with moving between different positions in the gravitational field of earth). From this initial relation, the student then inserts sets of other known relations – such as the fact that the change in gravitational potential energy (ΔGPE) is equal to the difference between the final gravitational potential energy (GPE_f) and the initial gravitational potential energy (GPE_i), and that gravitational potential energy itself is equal to $\frac{Gm_1m_2}{r}$ (glossed as the gravitational constant *G*, multiplied by the mass of the satellite (m_1), multiplied by the mass of the earth (m_2), all divided by the distance between the satellite and the centre of the earth (r)). In the final line, the student rearranges the equation to simplify it for calculations further along in the text. This derivation brings together a complex network of technical meanings and relates them precisely in terms of their interdependencies.

The specific relations in this derivation are not important for our discussion. What is important is that through the manipulation of mathematical symbolism the student is able to move from one set of relations, $work = \Delta GPE$, to a new set of relations $work = Gm_1 m_2 \left(\frac{1}{r_i} - \frac{1}{r_f}\right)$. In effect, the student has established new sets of interdependencies in the field; they have established relations not previously assumed (at this level, or at least logogenetically in this text), and in doing so, they have more tightly integrated the technical meanings of physics. In terms of LCT Semantics, derivations function to strengthen the semantic density of the discipline. They enable new relations to be established, which integrate an increasingly wide range of technical meanings. This means that any particular meaning specified in the derivation can now resonate out to all other meanings mentioned. But more than this, each term can be linked to other, unstated technical meanings by virtue of their relation any other symbol that is mentioned. This is powerful means of strengthening semantic density, and one that appears to be increasingly relied upon as students move into higher levels of physics.

A little before derivations are introduced, students become familiar with another genre of mathematics known as a quantification. Where derivations build new, previously unknown relations, quantifications measure a particular property by numerically quantifying it. In terms of field, Doran and Martin (chapter 5 of this volume) refer to the numerical measurement of properties as *gauging*. An example of this can be seen in the student exam response immediately following the derivation discussed above. Drawing on the final result of the derivation, the student inserts a set of numbers given in the question to calculate the work done in a particular situation:

$$[W] = Gm_1m_2\left(\frac{1}{r_i} - \frac{1}{r_f}\right)$$

$$= 6.67 \times 10^{-11} \times 1428.57 \times 5.97 \times 10^{24}\left(\frac{1}{6\ 380\ 000} - \frac{1}{6380000 + 355000}\right)$$

$$\doteqdot 4699722327$$

$$\doteqdot 4.70 \times 10^{9}\ \text{J (3 sig fig)}$$

Here, through numerous steps (detailed in Doran 2018), the student concludes that the work done is approximately 4.70×10^9 Joules (~ 4.7 billion Joules). What is significant about this text is that the quantification has enabled the student to relatively precisely measure a specific instance of a property. It has, in other words, taken the relatively generalized relations given in the symbolic equations and applied them to a specific situation. The quantification genre has moved the text from the relatively weak semantic gravity descriptions of general relations between properties in physics, to relatively strong semantic gravity measurements of an individual property tied to a very specific situation.

The two mathematical genres, derivation and quantification, thus enable students to strengthen semantic density and strengthen semantic density – to build theory and to link this with the empirical world. Symbolic equations such as $V=IR$ are not tied to any particular instance. Rather, they describe abstracted relations that encapsulate an innumerable number of instances. In this sense, they maintain relatively weak semantic gravity. At the same time, they realize a definite set of technical relations between highly technical symbols and so involve relatively strong semantic density. Symbolic equations can thus be positioned in the rhizomatic code (SG–, SD+). Derivations progressively pull together more and more relations between an ever-widening number of technical symbols, but they do so in a way that is not heavily tied to any particular context or situation – they remain relatively generalized. In this sense, derivations strengthen semantic density of the field, while having little effect on semantic gravity.[iv] Derivations can therefore be described as strengthening semantic density *within* the rhizomatic code (moving rightwards on the semantic plane). On the other hand, quantifications move texts from relatively weak semantic gravity relations that describe a wide range of phenomena to measurements tied specifically to a single instance. This means they significantly strengthen semantic gravity of the text. At the same time, they do this without decreasing the complexity of this knowledge. Moving from $[W] = Gm_1m_2\left(\frac{1}{r_i} - \frac{1}{r_f}\right)$ to $W \doteqdot 4.70 \times 10^9$ J (3 sig fig) does not move us into the realm of everyday, common-sense meanings. The meanings maintain relatively strong semantic density by virtue of the fact that the meanings being quantified (i.e. the units of measurement and the organization of this measurement) are all highly technical and resonate out to the much wider disciplinary knowledge of physics. But they do so while significantly strengthening semantic gravity. In this sense, quantifications enable mathematics to move from *rhizomatic codes* into *worldly codes* – to move from theoretical to empirical (rather than from theory to the 'everyday'). This shows that the description of physics as a relatively 'abstract' discipline (e.g. Kolb 1981) misses a key component of its knowledge, namely that it enables increasing complexity of knowledge while shifting from 'abstract' theory to grounded empirical measurements. These movements in semantic gravity and semantic density through mathematics are shown in Figure 7.3.

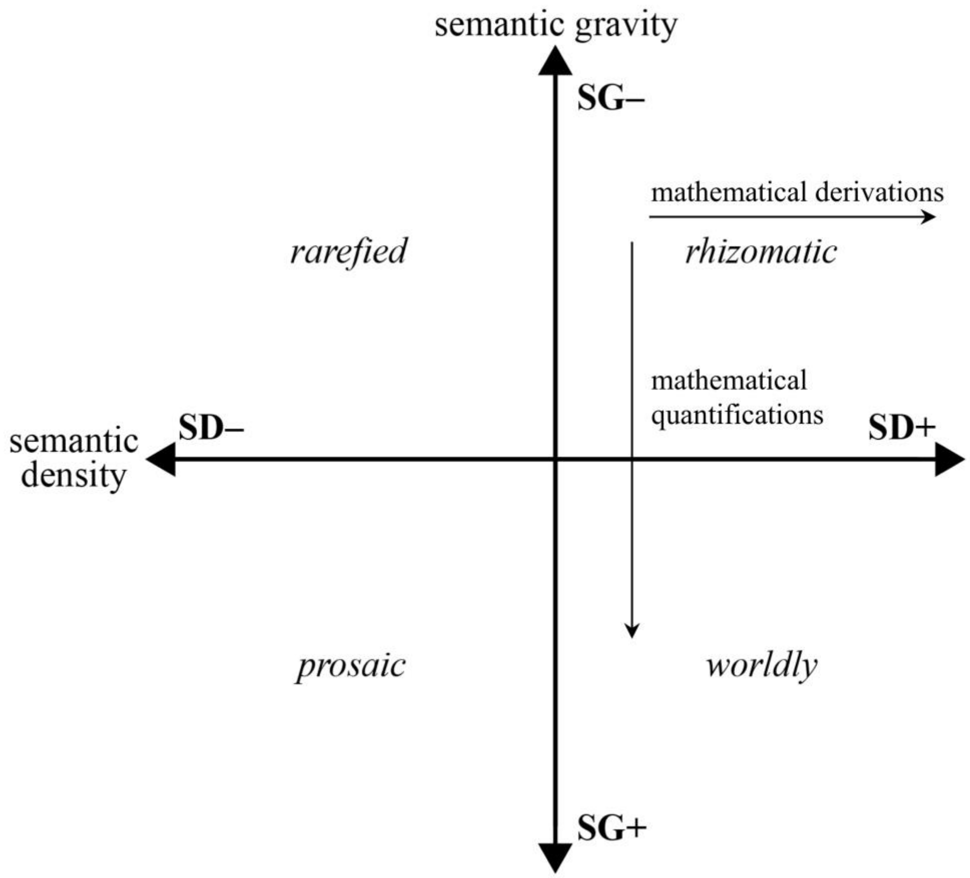


Figure 7.3. Movements in the semantic plane through mathematics

For students learning this knowledge, the use of mathematics complements the trained gaze developed in language. In addition to the movements shown in language from a prosaic code (SG+, SD–) to a rhizomatic code (SG–, SD+), the discipline emphasizes the importance of both continually strengthening semantic density *within* the rhizomatic code and being able to reach down to the empirical (worldly code or SG+, SD+), without moving into the common-sense. This has two effects. First, it emphasizes regular movement: the scientific gaze it is exhibiting is not one of static technicality or abstraction but of constant movement between the everyday, the theoretical and the empirical. Second, it emphasizes the utility of theoretical knowledge in terms of its ability to reach down and make precise predications about and descriptions of the empirical world. Such movements are vital for conceptualizing new situations from a scientific viewpoint.

This raises the question of how empirical meanings (SG+, SD+) can reach back to the theoretical meanings (SG–, SD+). We have seen that mathematics enables students to reach toward empirical description by quantifying individual properties but we have not yet seen how physics can use empirical measurements to change theory. In terms of semantic gravity, mathematics enables physics to strengthen semantic gravity (and to move from rhizomatic codes to worldly codes) but it offers no way at this stage to weaken semantic gravity again (to move back from worldly codes to rhizomatic codes). To deal with this issue, physics brings in images – specifically graphs.

KNOWLEDGE THROUGH IMAGE

Images occur throughout science (Parodi 2012, Lemke 1998). They enable a large number of meanings to be brought together and presented in a single, synoptic snapshot (Doran 2019, Martin *et al.* 2021). We can see this in the diagram in Figure 7.4, from the same student exam response as the mathematical examples above. In this question, the student was asked to *Draw a labelled diagram of the vacuum tube used by Thomson to calculate the q/m ratio of electrons.*

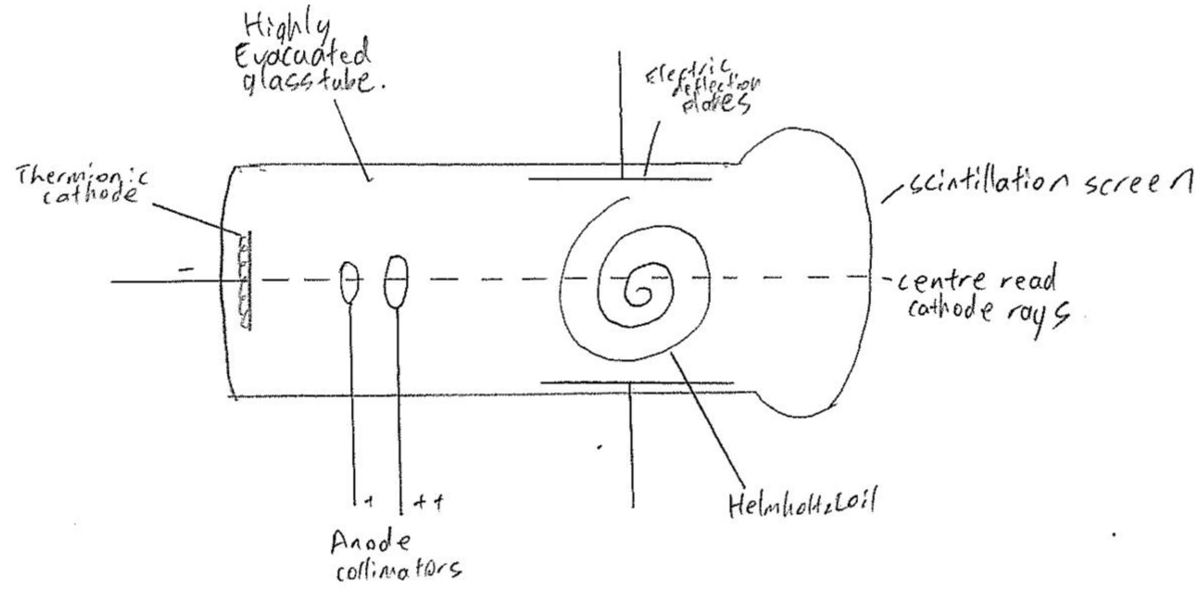


Figure 7.4. Diagram of an experimental apparatus

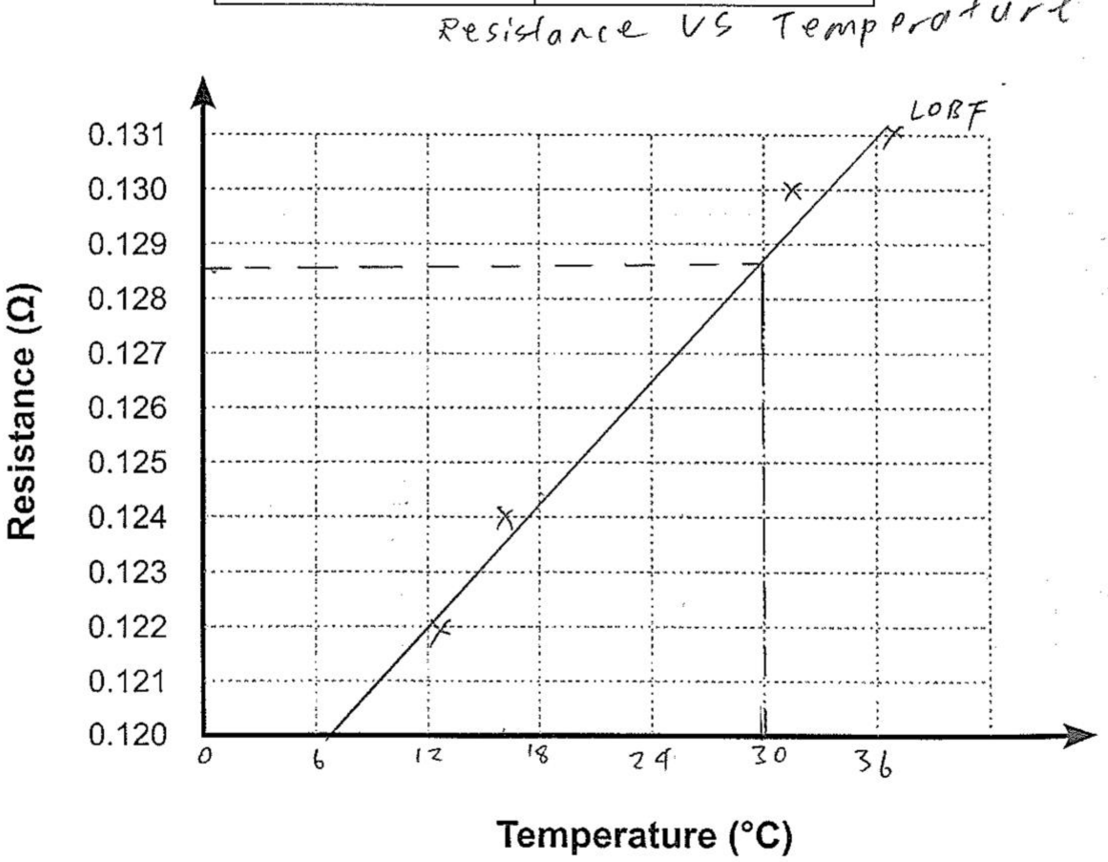
From the perspective of field, the diagram depicts a compositional taxonomy, in which each component is positioned as a part of the apparatus (the whole). However the diagram does not just present the various parts without any sense of how they come together to make the whole, what Kress and van Leeuwen (2006) call an *unstructured analytical* image. Rather, the components are spatially arranged in relation to one another – known as a *spatially structured* analytical image. In terms of the field relations of Doran and Martin (chapter 5, this volume), this means each component of the image realizes two distinct meanings: its part within a compositional taxonomy and its spatial position in relation to all the other parts in a spatial array.[v] The image also depicts activity through the dotted line labelled *centre read cathode rays*. Although there is no arrow or other overt indicator of a vector, the linear arrangement of the terms *cathode* and *anode* – as technical meanings in this field – are enough for an informed reader to understand the movement of the cathode rays is from left to right.

This diagram thus integrates three distinct dimensions of field: a compositional taxonomy incorporating each part of the apparatus; a spatial array that arranges the parts of the apparatus in relation to one another; and an activity involving a cathode ray that moves through the apparatus. It is difficult for either language or mathematics alone to bring together this wide range of meaning in one snapshot. Indeed this is one of the key affordances of images: they are able to pull together a large number of complementary meanings in a synoptic 'eyeful'. Diagrams in this sense are a key resource for packaging up multiple meanings to be read and viewed together. In terms of LCT, they offer the potential for significantly stronger semantic density in a way that complements that of language and mathematics.

As students move further into physics study, these diagrams are typically complemented by graphs. Graphs offer a relatively unique affordance in physics in comparison to the other resources we have seen so far and appear to be especially prevalent as students engage more deeply with experimental investigations. In terms of their knowledge-building potential, graphs complement mathematical quantifications by enabling a more flexible interaction between empirical measurements and more abstract theory. We can see this by exploring Figure 7.5. This figure displays a question from the same high school student exam response as the diagram and the mathematical examples above. The prompt includes a table of measurements for Resistance and Temperature of a wire. The question asks the student to: (1) plot these values on the graph (shown by the 'x's on the graph); (2) draw a line of best fit (that generalizes across the 'x's, shown by the line labelled LOBF); and (3) use this line of best fit to estimate the resistance of the wire at 30ºC (shown below the graph).

The electrical resistance, R, of a piece of wire was measured at different temperatures, T. Near room temperature, the resistance of the wire can be modelled by the equation $R = mT + b$.

Temperature (°C)	Resistance (ohms)
12.5	0.122
16.4	0.124
32.6	0.130
36.5	0.131



(a) Plot the data points on the graph provided. Draw a line of best fit on the graph and use it to estimate the electrical resistance of wire at 30° C.

using extrapolation ≑ 0.128.5 Ω
≑ 0.129 Ω (3 sig fig).

10

Figure 7.5. Graph and questions in a senior secondary school examination

From the perspective of field, the graph is organized around two properties presented on the axes (Resistance and Temperature) which are given measured values in the table above the graph. The first task of the student is to take these measurements in the table and plot them on the graph (shown by the ‘x’s on the graph). From the perspective of LCT Semantics, these plotted measurements show relatively strong semantic gravity. Each point describes a very precise instance that cannot be generalized to any other. But, like the numerical measurements in quantifications, they also exhibit relatively strong semantic density as they signify the intersection of two technical properties and are measured with the particular units of these properties (Ohms for Resistance, Degrees Celsius for Temperature).

The next step for the student is to draw a ‘line of best fit’. This involves generalizing across the plotted points to draw a line that ‘best fits’ each of the values. In this case, this is a straight line drawn from about six degrees Celsius on the temperature scale to the left, up to the about 37 degrees in the top right. Like mathematical equations, this line realizes a general interdependency between properties. It shows that when resistance increases, so does temperature (and vice versa). Similarly, this line has significantly weaker semantic gravity than the individual plotted points. Rather than being tied to any actual instance, the line develops a more generalized description. Indeed, the line does not intersect precisely with any of the measured points. Drawing a line of best fit weakens semantic gravity such that the relations it describes are not dependent on any particular instance or context.

By shifting between measured points and generalized lines of best fit, graphs can be used to shift from stronger semantic gravity to weaker semantic gravity while maintain relatively strong semantic density. They thus complement mathematical quantifications by allowing for students to shift from the worldly code back into the rhizomatic code. They enable a shift from the ‘empirical’ back up to the ‘theoretical’.

An important feature of images is that they do not insist on a definite reading path (Bateman 2014). In the case of graphs, this means students do not just have to move from measured points to generalized lines (from stronger to weaker semantic gravity). They can also use the generalized line to predict specific instances. Indeed this is the third task the student is asked to do, when question (a) says to *estimate the electrical resistance of wire at 30º C.* To answer this question, the student would have to find where the line of best fit is at 30º C, and 'read off' the value of the Resistance at this point. In this example, the student has done this by drawing two dotted lines, one vertical line at 30º Celsius, and then one horizontal line at around .1285 Ohms Resistance. Below the graph, the student then rounds this up to 0.129 Ohms. In terms of semantic gravity, this displays a movement back from weaker semantic gravity to stronger semantic gravity. The student begins with the generalized description shown by the line of best fit and uses this to make a prediction of a specific measurement. Although this is an estimation, the prediction is strongly dependent on a context where the wire is 30ºC, and so it displays relatively stronger semantic gravity.

This example illustrates how graphs enable movements back and forth between stronger semantic gravity and weaker semantic gravity. This affordance makes it a key tool for organizing the knowledge of physics (and many other disciplines). Figure 7.6 illustrates this movement. Where mathematical derivations enable movements within the rhizomatic code, and quantifications organize one-way trips from the rhizomatic code to the worldly code, graphs give opportunities for shifts back and forth – what Maton and Howard (2018) term 'return trips'.

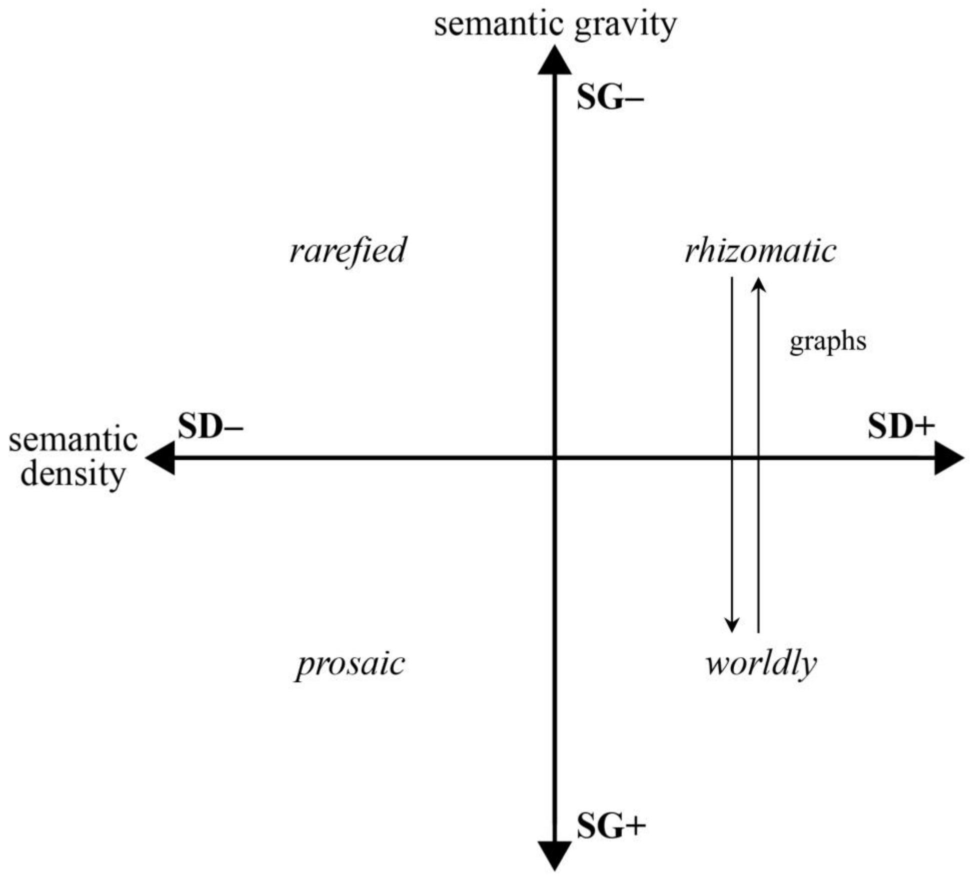


Figure 7.6. Movements in the semantic plane through graphs

MULTIMODAL KNOWLEDGE

We can now return to the original question of this chapter: what knowledge do students need to learn in order to be successful in science? In the first instance, they need to understand the technical content meanings of the discipline. From the perspective of field, this means marshalling various items, activities, properties, and their respective relations when necessary. As this chapter has shown, this necessarily implicates multiple semiotic resources. Mathematics is able to bring together rich interdependencies between properties and measure these quantitatively; graphs are able to establish multiple arrays upon which measurements can be ordered; and diagrams and language can integrate a wide range of different types of meaning, including taxonomy, activity and property. The content meanings of science are organized through the multimodal resources of science.

In the second instance, students need to learn a particular way of seeing the world. This way of seeing the world does not simply involve technical discussions of abstract phenomena. More importantly, it involves moving between the ‘common-sense’ and the ‘technical’, the theoretical and the empirical. In terms of LCT Semantics, this means being able to move between a prosaic code (SG+, SD–) and a rhizomatic code (SG–, SD+), and between a rhizomatic code and a worldly code (SG+, SD+). Or, to put this another way, students need to be able to strengthen and weaken semantic gravity and semantic density independently and together. They need a way of seeing the world from various perspectives and shifting between these perspectives as needs arise. As mentioned above, what is at stake here is a trained scientific gaze. Being able to read and write particular the semiotic resources and field-specific meanings of science is not enough. Students need to be able to select and arrange these resources appropriately in potentially new scenarios. This means they need a way of understanding the organizing principles of the knowledge in any particular situation. For physics (and science more broadly), this necessarily involves using multiple semiotic resources. Language enables the common-sense to be repackaged as uncommon-sense (and vice versa); mathematics enables a steady increase in the complexity of meaning while also moving from the theoretical to the empirical; and images enable an integration of a wide range of meanings to increase complexity and movement back and forth between the empirical to the theoretical. In all, students must learn that scientific knowledge is multimodal.

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[i] The semantic density and semantic gravity explored in this chapter are those associated with 'content' meanings – technical procedures, logical reasonings, taxonomies etc. This is known as *epistemic–semantic density* and *epistemic–semantic gravity* (Maton 2014, Maton and Doran 2017b). This contrasts with *axiological–semantic density* and *axiological–semantic gravity* that explore meanings associated with values, political judgements, morals, aesthetics etc.

[ii] These were previously called implication *sequences* (e.g. Martin 1992). However, following Hao (2015, 2020) 'sequence' is reserved for relations between figures in discourse semantics, and 'implication' will be reserved for one type of relation between activities in a field. The relationship between a larger activity and the smaller activities that constitute it is known as *momenting* (discussed in Doran and Martin, chapter 5 of this volume).

[iii] More precisely, each symbol realizes an *itemized property* – a property reconstrued as an item. This is because they may be graded (like properties), but they can also be classified (like items). For example, one may have more or less E (energy) (interpreted as a property), but one may also distinguish between different types of energy, such as initial energy, E_i, final energy E_f and average energy E_{av} (interpreted as items in a classification taxonomy). See Doran and Martin, chapter 5 of this volume for discussion.

[iv] It is possible that particular derivations may strengthen or weaken semantic gravity by either deriving a set of relations only applicable to more precise situations or conversely deriving more generalized relations to cover a wider set of phenomena. This would be a function of the particular derivation under study rather than all derivations in general.

[v] More precisely, each element realizes a position along two spatial arrays, one vertical and the other horizontal.