

Analytical Framework for Student-Generated Drawings

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Abstract

This article presents the development, description, application, and discussion of an analytical framework to examine students' drawings of scientific concepts and processes. Student-generated representation, particularly drawing, is increasingly emphasised as an important learning strategy to help students reason, explain, and demonstrate their scientific thinking and understanding. Although this strategy would require a greater need to understand what students are drawing, there are currently few frameworks that can support researchers and educators in analysing student-generated drawings. Based on the theory of social semiotics and an empirical data corpus of students' drawings from two research projects, we developed an analytical framework to describe and categorise a broad range of ideas and relationships that students are representing through their drawings in physics and chemistry. The application of this framework will be illustrated by two analytical examples of students' drawings in the topics of rotational moment and chemical bonding. The first example analysed students' drawings in relation to their accompanying written explanations, while the second example analysed the students' drawings in conjunction with the occurring classroom discourse. Through the illustration, the research and pedagogical applications and usefulness of this analytical framework will be discussed.

Keywords: Visual analysis, drawing, multiple representations, student-generated representations, learning with representations, multimodality, social semiotics

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Introduction

Visual representations (e.g., drawings, schematics, animations, graphs) are indispensable to scientific thinking and learning. Learning how to interpret and draw conventional scientific diagrams (e.g., force, circuit, particle model, cell structure) has been an important part of the science curriculum. In recent years, there is a growing focus on the use of students' drawings as a learning and reasoning strategy to support pedagogies to guide students in generating, refining, and justifying representations in science (e.g., Quillin & Thomas, 2015; Prain & Tytler, 2012). At the same time, representations are increasingly used to support the learning of scientific practices such as modeling, explanation and argumentation (e.g., Oliveira, Justi, & Mendonça, 2015; Namdar & Shen, 2016). This recent focus on student-generated drawings reflects a growing theoretical understanding among science education researchers on the role of representations to support learning *with* representations, rather than learning *from* representations (Tang, Delgado, & Moje, 2014).

Despite the focus on student-generated representations, there are currently few analytical frameworks that can be used to examine students' drawings. Researchers have thus far developed frameworks focusing on: (a) classification of representations (e.g., Ainsworth, 2006; Hegarty, Carpenter, & Just, 1991), (b) analysis of print images in science textbooks (e.g., Ge, Unsworth, Wang, & Chang, 2018; Meneses, Escobar, & Véliz, 2018), (c) analysis of multiple and multimodal representations used in classrooms (e.g., Tang, 2016; Tang et al., 2014; Prain, Tytler, & Peterson, 2009) and assessment of students' drawing and writing as a multimodal unit (e.g., Wilson & Bradbury, 2016). However, none of these frameworks specifically addresses how to analyse students' drawings in science.

A framework to analyse students' drawings should ideally describe and categorise a broad range of ideas that students are representing. Not only can the framework provide a systematic and comprehensive way of examining students' drawings and the ideas that are represented by the drawings, it can also guide the analyst in interpreting students' reasoning and understanding that are contextual to the subject matter. Having such a framework will be the first step toward developing a tool that will support teachers to use students' drawings in the teaching and learning of scientific concepts and practices. With a focus on meaning making, the goal is to help teachers understand how students make scientific meanings through their drawings and consequently design appropriate instructional scaffolds with the use of visual representations to mediate their learning.

The purpose of this paper is thus to present and illustrate an analytical framework on students' self-generated drawings that were collected over several years in two research projects. The development of the framework, which consists of several levels and categories of analysis, will first be presented and explained. It will then be applied to analyse students' drawings in two specific topics – rotational moment in physics and chemical bonding in chemistry. The physics example illustrated how the students' drawings was analysed in relation to their accompanying written explanations and the chemistry example illustrated the visual analysis in conjunction with the occurring classroom discourse (with speech and gesture). Both analyses will be used to illustrate and discuss the research affordances and application of the analytical framework.

Theoretical Perspectives

Social Semiotics

The theoretical basis of the framework presented in this paper is informed by social semiotics, which is a theory developed to understand how people use various semiotic systems such as language and images to make meanings in a discourse community (Halliday, 1978; Lemke, 1990). In particular, three key concepts from social semiotics form the theoretical underpinnings of this study, namely *semiotic system*, *text* and *choice*.

A *semiotic system* is an accumulation of culturally shaped signs that are developed and used by a community as resources for making meaning. According to Halliday (1978), every semiotic system has evolved and continues to evolve as a system of signs organised according to the interests and communicative needs of a particular discourse community. Thus, a visual system – consisting of images and diagrams, evolves as an accumulation of the way a particular community uses and shapes visual resources in order to make certain meanings demanded in that community (Kress & van Leeuwen, 2006). As the communicative needs of various discourse communities are different, multiple visual systems have been developed that are specific to the needs of particular disciplinary areas, such as art and mass media (O'Toole, 1994), architecture (O'Toole, 2006), and of course science (Lemke, 1998).

While a *semiotic system* is an accumulation or network of all possible signs that are available as meaning-making resources for a community, a *text* is a particular instance of how the signs are produced to make meaning in a specific context. The relationship between a system and text is dialectical and mutually constitutive. For example, just as the semiotic system of language affords and constrains what we can write in any text, the production of texts over many instances can in turn affect the larger network of how written language is used, and consequently change the system over time. This is how the English language as a system has evolved and will continue to evolve. In social semiotics, the term 'text' is not limited to a stretch of written language, but is generalised to any inscription produced by its corresponding semiotic system.

Besides explaining the evolutionary development of semiotic systems and representations at a phylogenetic (community) level, social semiotics also accounts for how meanings are made through representations at an ontogenetic (individual) level. From a learning development point of view, the representations encountered by a user aggregate to become a repertoire of resources for him or her to draw upon in future to make meanings in new encounters. This is consistent with how Vygotsky (1986) had theorised the relationship between language and cognitive development, whereby the representations (e.g. words, images) learned on a social plane are internalised to become the basis of our thought process and development of scientific concepts (Tang, 2011). Through this relationship between representation and conceptual understanding, learning is therefore an iterative "process of sign-making" (Kress, Jewitt, Ogborn, & Tsatsarelis, 2001) where students make use of available representations to generate new understanding, and at the same time, make new representations based on their new understanding. In this sense, representations serve as both an enabler and evidence of content learning.

How a user selects semiotic resources to make meanings in their drawings in any particular instance is explained by the notion of *choice*, which is influenced by two different factors. The first factor is related to the semiotic system where the choice of any sign with the system will afford and limit the types of meaning that could and could not be made. For instance, in a study by Tang et al. (2014), they reported that the choice of drawing a piece of sandpaper from a side-view perspective as opposed to a top-view perspective (within a visual system) allows a group of seventh graders to represent depth and consequently use this analogy to explain bacterial residue on surfaces. On the other hand, students who chose a top-view diagram could not sufficiently explain the same concept because they had no way of visualising and representing depth. The second factor is related to the interest of the user, or sign-maker, in terms of selecting features from a semiotic system that are salient or apt in expressing what he or she has in mind through words, images or other representations (Kress & van Leeuwen, 2006). As such, every sign made by a user is meaningful and it reflects the choices made in relation to the (a) relative affordances of the semiotic systems, and simultaneously, (b) the interest and intention of the sign-maker. In sum, analysing these choices can reveal how a person thinks about and portrays an aspect of reality in a particular way using the semiotic resources that are available.

With these theoretical underpinnings, we consider diagrams as a semiotic *system* of culturally shaped signs developed as meaning-making resources (see Tang, 2013). By analysing students' diagrams as *texts* that derive from the system, we can infer the meanings and ideas they had based on the *choices* they made to produce those texts.

Visual Analysis

Social semiotics has been used not only to provide a theoretical account of meaning-making, but also applied to develop analytical tools for analysing representations in multiple semiotic modes (e.g., Halliday, 1994; Kress & van Leeuwen, 2006; O'Halloran, 2000; O'Toole, 1994). According to Lemke (1998), any representation, whether it is a written text of words or a drawing of lines and shapes, simultaneously makes three general types of meaning¹: (a) presentational meaning to present our ideas and experiences about the world; (b) orientational meaning to enact our interaction and relationship toward the world and other people; and (c) organisational meaning to connect and organise separate elements together into a larger and coherent representation.

In the analysis of images, Kress and van Leeuwen's (2006) 'grammar of visual design' is a pioneering work that provides a useful framework for researchers to analyse visual representations. However, Kress and van Leeuwen's (2006) framework was developed from their analysis of visual images in multiple disciplines (e.g., art, media studies, social studies, science & technology) and media format (e.g., paintings, photographs, film, schematic diagrams, colour print, computer graphics, maps). Although there are some examples of images used in science, many categories in the framework are not directly

¹ In the context of language analysis, Halliday (1994) calls the 3 types of meanings *ideational*, *interpersonal* and *textual* meanings, while in image analysis, Kress & van Leeuwen (2006) call them *re-presentational*, *interactive* and *compositional*. We chose Lemke's (1998) taxonomy as it is the most widely used within science education.

applicable to science education nor sufficiently extensive to capture the nuances of student-generated drawings in science. Furthermore, as the framework was developed for linguists and semioticians, it is inaccessible for researchers and educators to understand and apply in science education. For this reason, it was necessary to develop a new framework that suits our purpose of analysing scientific diagrams drawn by students. We therefore recontextualised Kress and van Leeuwen's framework based on a data corpus of students' drawings in high school physics and chemistry. Notably, we refined several categories in their framework and developed new categories in order to make them more relevant to scientific diagrams and more accessible to science educators.

Methods – Development of Analytical Framework

Context of Data Sources

The data that were used to develop our framework were based on two research projects in Country A and Country B (blinded for peer review purpose) that focused on student drawings as part of a teaching intervention to improve student learning of science concepts. The interventions in both projects involved the use of a Predict-Observe-Explain strategy (White & Gunstone, 1992) where the students predicted the outcome of a demonstration before they observed and explained the phenomenon. They were then asked to draw and write their predictions and explanations. As the students had not learned the scientific concepts and explanations for the topic under investigation, their drawings and written explanations reflected their prior understanding of the subject matter (See Tang, Ho, & Putra, 2016; Treagust, Won, & McLure, 2017). Four teachers and 106 grade nine students participated in the first project while two teachers and 119 students participated in the second project.

The participating students in these two projects produced many diagrams as part of the interventions. The diagrammatic data from those projects provided a corpus to create the analytical framework proposed in this paper. In addition to covering a wide range of topics (e.g., Newton's Laws, forces, moment, density, wave, sound, kinetic theory of matter, chemical bonding, qualitative analysis, redox, electrolysis) for secondary school science, the diagrams from those projects were generated by students across a range of ability groups under a variety of instructional tasks. As such, the diversity in the diagrams is suited for establishing a broad framework to analyse students' diagrams under various cultural and pedagogical circumstances. For this study, a total of 594 scanned diagrams were collected and organised in relation to the year level and science topic for further analysis.

Analytical Procedures & Development

The development of the framework involved an iterative cycle between a top-down perspective informed by theory and a bottom-up grounded inquiry based on data. Informed by Lemke's (1998) theory (based on Halliday's work) that all semiotic systems make 3 types of meaning – presentational, orientational and organisational, we developed a set of categories for each type of meaning. There are altogether seven main categories in the framework, namely *association*, *spatial*, *movement*, *perspective*, *modality*, *connective*, and *textual contextualisation*. *Association*, *spatial* and *movement* focus on presentational

meaning, *perspective* and *modality* focus on orientational meaning, while *connective* and *textual contextualisation* focus on organisational meaning. Most of these categories also have sub-categories that further specify the various aspects of a main category. See Table 1 for a list of the categories/sub-categories.

Table 1. Categories and Sub-categories in the Framework (See Table 2 to 8 for elaboration and examples)

Types of Meaning	Main Category	Sub-category
Presentational	Association	---
	Spatial	Position Alignment Spacing Distribution Relative size Relative scale
	Movement	---
Orientational	Perspective	Dimension Angle Abstraction
	Modality	Formality Simplicity
Organisational	Connective	Temporal Sequence Comparison
	Textual contextualisation	Label Legend Caption

For each category/sub-category, there is a range of relationships that denote a distinguishable feature or method of how an image is drawn under a particular category/sub-category. As explained in the theoretical section, relationships are the “choices” made by the students in selecting their repertoire of visual resources to represent their ideas. It is important to note that categories/sub-categories are not mutually exclusive, i.e., a diagram can exhibit many categories/sub-categories at once. However within a category or sub-category, relationships are mutually exclusive, i.e., once a choice has been made with regard to selecting a particular visual resource, alternative choices will be precluded. See Tables 2 to 8 for the list of relationships and examples for each category.

In the process of reviewing and adapting the literature (e.g., Kress & van Leeuwen, 2006), the first author generated a tentative list of analytical categories and sub-categories (as described above), which was then used to examine the students’ diagrams in the data corpus. Against each category/sub-category, commonalities and differences among the students’ diagrams were examined to distil any distinct patterns and characterisations. Through this process, the various relationships for each category/sub-category were generated. Thus, the set of these relationships emerged from an inductive and systematic analysis of the data corpus, rather than developed a priori based on the literature. In an iterative manner, the set of categories/sub-categories and relationships were then refined, expanded, collapsed, and

consolidated to reflect the main features of student-generated diagrams in science. This process was repeated several times until a suitable framework that covered the data corpus emerged (Lincoln & Guba, 1985).

From this emerging framework, the first and second authors then went through each category in relation to its description and usefulness in analysing students' diagrams. They applied the framework to specific topics covered in the data corpus to assess its applicability. In particular, the framework was used as a coding scheme to analyse students' diagrams in these topics and spreadsheets were created to compare the frequency for various relationships in every category/sub-category. This process helped us to determine the relevance and usefulness of the framework for different topics, as well as test the robustness of the framework as an analytical coding scheme. At the same time, both authors also separately checked on each other's codes in order to establish a common interpretation. Any ambiguities were discussed and resolved collectively, which occasionally also involved modifying the analytical categories and sub-categories when necessary.

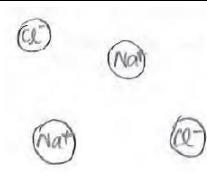
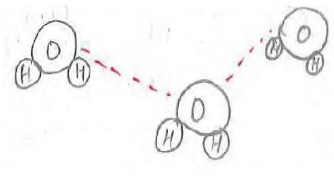


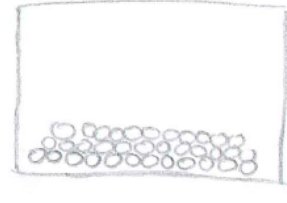
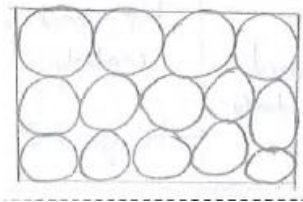
Results – Description of Analytical Framework

Association

The first category in the framework examines how the visual “objects” depicted inside a drawing are associated to one another through lines, proximity or other means that visually join them together. A visual object can be identified from its completeness and isolation from other objects in a drawing. The most commonly depicted objects are circles, boxes and other geometrical shapes that form the basic building blocks comprising the drawing. Using a linguistics analogy based on Halliday's (1978) systemic functional linguistics (SFL), these shapes function as the “participants”, as expressed by nouns in a sentence, that represent things in the natural world. By analysing how these shapes are joined together, we can infer the kind of relationships between the things or participants that the drawer has in mind visually. We identified 5 possible relationships that can be depicted in *association*: *independent*, *connecting*, *adjoining*, *intersecting* and *inclusive*. *Inclusive* relationship can be further divided into *partial* inclusion, where the larger object is partially filled up by the smaller objects, leaving a lot of blank spaces, and *exhaustive* inclusion where the larger object is completely filled by the smaller objects (See Table 2 for an explanation and example of each of these relationships).

The relationships under *association* are mutually exclusive, that is, if a relationship between two objects is *adjoining* (touching boundaries), it cannot simultaneously be *independent*, *connecting*, *intersecting* and *inclusive*. However, most drawings usually contain more than two objects, and in such cases, there can be multiple associative relationships in a diagram, one for each pair of visual objects. For example, in a drawing of water vapour molecules, there will be one set of relationships between hydrogen and oxygen atoms (*adjoining* or *intersecting*), one set of relationships between H₂O molecules (*independent* or *connecting*), and one set for the H₂O molecules and the enclosing space (*inclusive*).

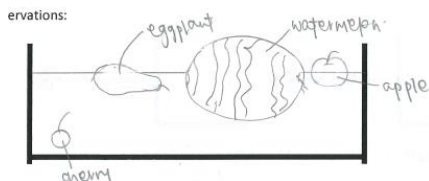
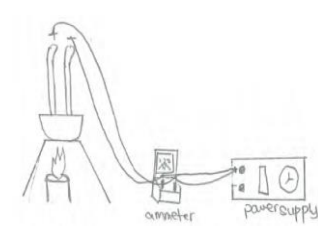

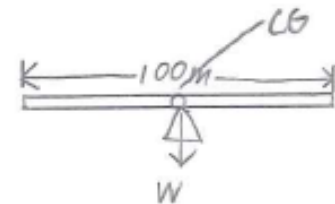
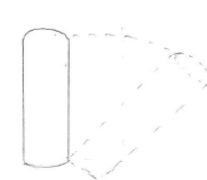
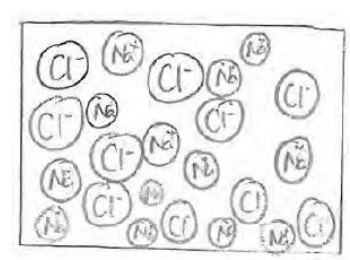
Table 2. The Category of Association

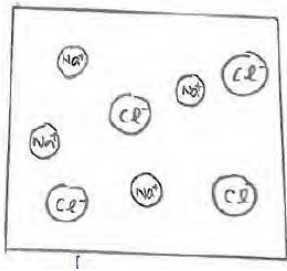
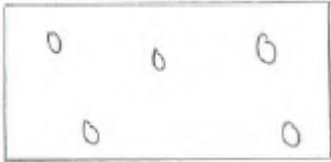
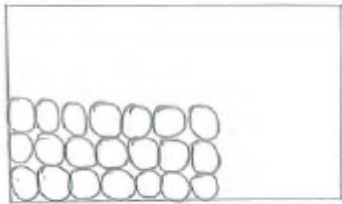
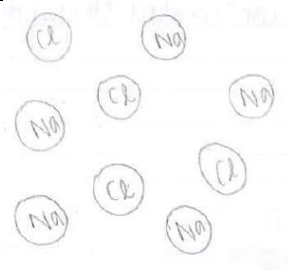
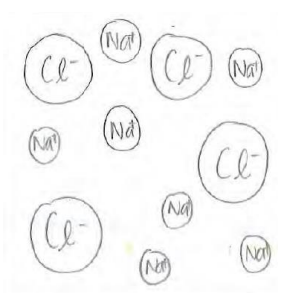
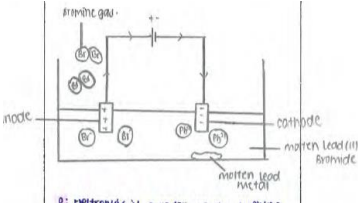

Category	Sub-category	Relationship	Examples
ASSOCIATION – Examine how 2 or more visual objects are <u>joined together</u> to each other	None	Independent – The objects are not joined together	
		Connecting – The objects are joined together through lines	
		Adjoining – The objects are joined together through touching boundaries	
		Intersecting – The objects are joined together through overlapping boundaries	
		Inclusive – An object or objects are drawn within a larger object	<div>Partial</div> 
			<div>Exhaustive</div> 

Spatial

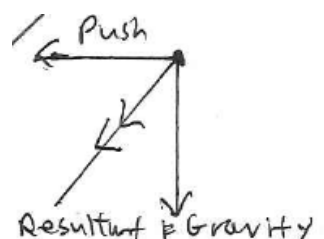
This category in the framework examines how the visual objects depicted in the drawing are related to one another spatially through six sub-categories: *position* of the visual objects (top, bottom, left, right), *alignment* of the objects (parallel, angle, perpendicular), *spacing* (close or distant between objects), *distribution* (random or patterned arrangement among objects), relative size (object size in relation to one another) and *relative scale* (how spatially accurate the objects are in terms of their position, size and spacing). See Table 3 for further explanation and examples.

Table 3. The Category of *Spatial*

Category	Sub-category	Relationship	Examples
SPATIAL – Examine how 2 or more visual objects are related to each other <u>spatially</u>	Position	Top-Bottom – The objects are positioned top to bottom	
		Left-Right – The objects are positioned left to right	
	Alignment	Parallel – The objects are aligned in parallel	
		Perpendicular – The objects are aligned at an right angle	
		Angle – The objects are aligned at an oblique angle	
	Spacing	Close – The objects are close to one another	

	<p>Distant</p> <p>– The objects are far away from one another</p>	
Distribution	<p>Random</p> <p>– The objects are distributed randomly in the space</p>	
	<p>Pattern</p> <p>– The objects are arranged in a patterned distribution</p>	
Relative size	<p>Similar</p> <p>– The objects are of similar size to one another</p>	
	<p>Distinct</p> <p>– The objects are of distinct size to one another</p>	
Relative scale	<p>Exaggerate</p> <p>– The size and position of some objects are exaggeratedly drawn out of proportion</p>	
	<p>Realistic</p> <p>– The size and position are realistic drawn with relative spatial accuracy</p>	

Proportional
– The size and
position are
drawn to scale



Movement

The third category examines how an object is drawn to depict any unfolding dynamic action or movement (See Table 4). Movement in drawings can be identified from the presence of a ‘vector’ formed by the depicted objects along a real or imaginary line (Kress & van Leeuwen, 2006). This vector serves to present some kind of action, transition or unfolding event. From our analysis of students’ drawings, we identified 3 usual methods in how movement are illustrated in the drawings: the use of *arrow*, *path line* and *wavy lines*.


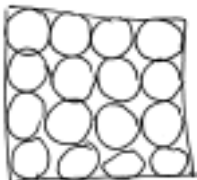
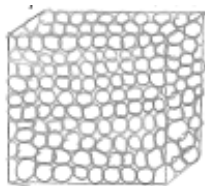
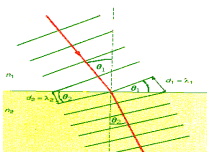
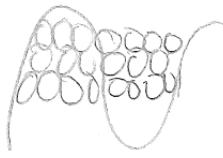
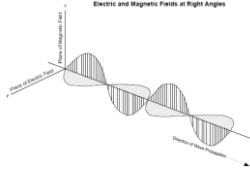
Table 4. The Category of Movement

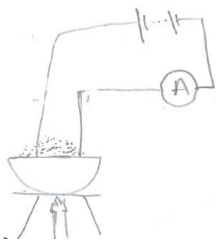
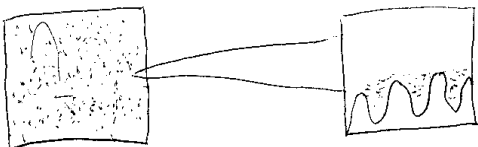
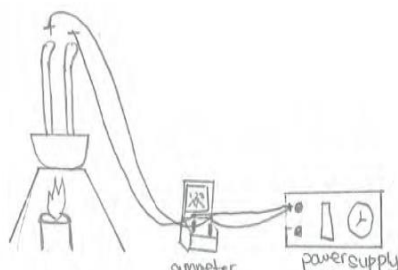
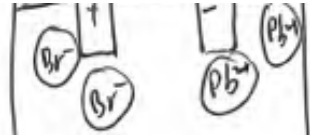
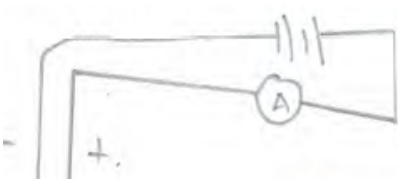
Category	Sub-category	Relationship	Examples
MOVEMENT – Examine how a visual object moves or acts dynamically	None	Arrow – using arrow to indicate direction of movement	
		Path line – using dotted line (or different color) to trace a previous position or path taken	
		Wavy lines – using short wavy lines around an object	
		No movement – no visual indication of movement	

Perspective

The fourth category is *perspective*, which examines the point of view of how a visual object is depicted (See Table 5). There are three sub-categories under *perspective*: *dimension* (1, 2 or 3-dimensions), *angle* (top, side, oblique, mixed or projected view), and *abstraction* (macroscopic, microscopic, symbolic). The sub-categories of *dimension* and *angle* should not be confused as a *spatial* category. While *spatial* sub-categories examine the spatial relationships among the depicted objects (representing an objective description of the things in reality), *dimension* and *angle* examine the spatial relationships between the *viewer* and depicted objects (representing a subjective view of how a viewer sees or wants the audience to see the constructed reality from a particular point of view). This is why perspective is an orientational meaning rather than a presentational one.

Table 5. The Category of *Perspective*

Category	Sub-category	Relationship	Examples
PERSPECTIVE – Examine the point of view of how a visual object is depicted	Dimension	1-dimension – portraying a 1D view of object	
		2-dimension – portraying a 2D view of object	 Solid
		3-dimension – portraying a 3D view of object	
	Angle	Top view – portraying a top view of object	
		Side view – portraying a side view of object	
		Oblique view – portraying an oblique view of object	

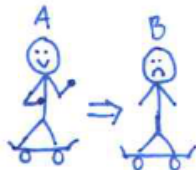
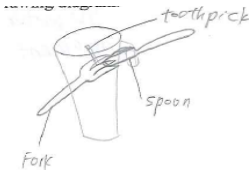
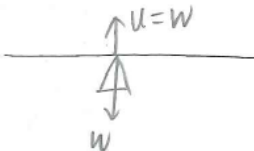
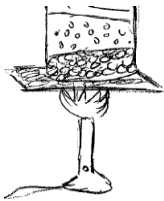

	<p>Mixed view – portraying a combination of top and side (or oblique) view of object</p> 
	<p>Projected view – portraying a magnified view of a small part of object</p> 
Abstraction	<p>Macroscopic – portraying a view seen with the naked eye</p>  <p>Microscopic – portraying a view that cannot be seen with the naked eye</p>  <p>Symbolic – portraying a view that is connected to the object based on social conventions</p> 

Modality

Another orientational meaning is *modality*, which reflects the credibility or truth value of a representation in terms of how close it resembles reality (See Table 6). As reality is constructed by the viewer and can be shaped by the way the representation is created by the author, modality is an orientational meaning instead of presentational. The modality of an image depends on the social discourse (Kress & van Leeuwen, 2006). In mass communication for example, we ascribe more credibility (higher modality) to a photograph as compared to an artistic sketch showing the same object or event. Thus, modality in mass communication is related to naturalistic realism. However, in scientific discourse, modality is linked to universality and objectiveness rather than its realism. Thus, black-and-white

schematic diagrams have a higher modality because they are applicable across localised settings. By contrast, photographs showing the same phenomena or experimental setup have a lower modality because they are seen as localised and limited to a particular laboratory. In the students' drawings, we identified two sub-categories of modality – *formality*, which examines the level of details and its perceived credibility and *simplicity*, which examines the style of drawing using shades and lines. Under these two sub-categories, schematic details with sharp lines are the highest form of modality.

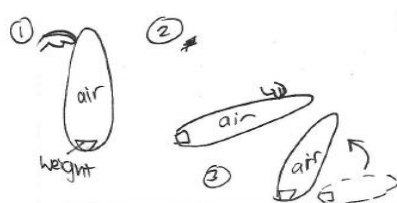
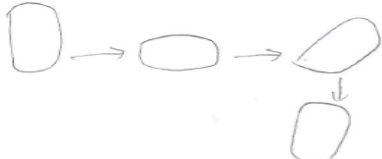
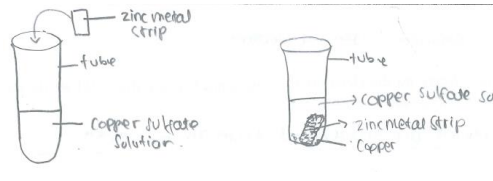

Table 6. The Category of Modality

Category	Sub-category	Relationship	Examples
MODALITY – Examine the truth value or credibility of how a visual object is depicted	Formality	Cartoonish – showing humor, exaggeration or caricature feature (low modality)	
		Iconic – showing observed objects based on resemblance	
		Schematic – showing bare essentials without irrelevant visual details (high modality)	
	Simplicity	Shades – drawn with shades or color to give a sense of realism (low modality)	
		Sharp lines – drawn with clear and continuous sharp lines with no color or background (high modality)	

Connective

Thus far, all the categories apply for drawings that show an object or cluster of objects at a particular instance. But what if a drawer needs to depict the passage of time or make some kind of comparison? This is where organisational meaning, focusing on how smaller textual/visual elements are organised to form a coherent representation, is relevant. One type of organisational meaning is *connective*, which examines how smaller visual elements are joined to make logical connections (See Table 7). These function similarly as connective words that are used to join clauses and sentences together. According to SFL (Halliday, 1994), there are four types of logical connections made by connective words, namely additive (e.g., and, in addition), temporal (e.g., next, then), comparative (e.g., however, while) and consequential (e.g., because, due to). In visual drawings, we identified only two types of visual connectives – *temporal* and *comparative*. *Temporal* sequences can be shown by *numbering*, *arrow* and *ordered juxtaposition* while *comparison* can be shown by *unordered juxtaposition* (side-by-side comparison). The use of *arrow* in *temporal sequence* can sometimes be easily confused with the indication of movement as explored in the earlier category, although it has a different function in denoting the passage of time rather than a spatial displacement of the object.

Table 7. The Category of *Connective*

Category	Sub-category	Relationship	Examples
CONNECTIVE – Examine how smaller elements within a complex diagram are joined together to make logical connection	Temporal Sequence	Numbering – using numbers to indicate time sequence of images	
		Arrow – using arrows to indicate passage of time	
		Ordered juxtaposition – using left to right or top to bottom sequence to indicate before and after	
	Comparison	Unordered Juxtaposition – comparing two or more images side by side	

Textual contextualisation

The last category accounts for how written texts, which often appear in students' drawings, are used to contextualise the meaning of a visual object. Written text can be used as a *label* (by *inclusion*, *proximal* or *indexical*) to indicate annotated diagrams, *legend*, or *caption* (See Table 8).

Table 8. The Category of Textual Contextualisation

Category	Sub-category	Relationship	Examples
TEXTUAL CONTEXTUALISATION – Examine the use of text to add or contextualize meanings to a visual object	Label	Inclusion – text inside an object	
		Proximal – text next to an object	
		Indexical – text joined to an object through a line or arrow	
	Legend	– text separated from the diagram and connected using same color, shape or symbol	
Caption	Caption	– longer text (phrases or sentences) for entire diagram, rather than individual objects	

Results – Application of Analytical Framework

To highlight the applicability of the framework, we examined a corpus of students' drawings and illustrated two examples from physics and chemistry in this section. The first example examined the students' drawings in relation to their accompanying written explanations, while the second example examined the students' drawings in conjunction with the occurring classroom discourse.

Illustration of Analysis in Physics (with Written Explanations)

The first example is based on a physics lesson on rotational moment. The lesson was designed around a learning station approach where small groups of students rotate through 5 stations that explored different phenomena (called scenarios) related to the concept of moment. One of the scenarios focused on a roly poly toy that can return to its upright orientation when pushed over, due to the position of its centre of gravity. As the students explored this station, each of them wrote an observation and initial explanation with the aid of a diagram (see Figure 1). After the students had completed all the scenarios, the teacher discussed the explanations with the whole class. Based on the discussion, each student then drew a refined diagram and wrote a refined explanation. In the case of the roly poly scenario, the teacher drew a diagram on the board, which was copied by most students onto their worksheets. The teacher's diagram (as shown in green on the bottom of Figure 1) provided a reference diagram for us to compare with the students' diagrams.

Activity Worksheet

Scenario 2: Roly poly

During activity/Observation	Post activity/ Explanation	
a. Write down your observation (after releasing the finger)	Explain your observation for part (a) with the aid of a diagram	
<p>The roly poly went back up to its original standing state without any force</p>	<p>Initial drawing/diagram:</p>	<p>Initial explanation:</p> <p>When the roly poly is pushed down and its parallel to the ground, once the effort is gone, the roly poly will return to its original state.</p>
	<p>Refined drawing/diagram:</p>	<p>Refined explanation:</p> <p>A moment is produced by the weight was shown in the defined diagram. As the roly poly is hollow with a weight at the bottom, it has a low centre of gravity as shown in the diagram. When the roly poly is pushed down, a moment is produced by the weight was shown in the diagram. Hence, the roly poly regains its original position.</p>

Figure 1. A sample of student's worksheet used in the physics lesson

Analysis of the students' initial drawings using the framework revealed several important distinctions related to the categories of *movement*, *connective*, *spatial* and *perspective*, as compared to the reference diagram. In *movement*, the majority of students (72%) depicted a sense of movement in the roly poly, with 24% using path line (e.g., Figure 2a) and 60% using arrow (e.g., Figure 2c). In *connective*, about half of the students (48%) drew multiple images of the roly poly to show a temporal sequence, with 20% using arrow (e.g., Figure 2b), 20% using ordered juxtaposition, and 8% of them using numbering (e.g., Figure 2c). The next category relevant to the analysis of the drawing is *spatial*, particularly on *alignment*. Most of the students (84%) showed multiple positions of the roly poly in 2 different alignments, either horizontal and vertical (i.e., perpendicular) or horizontal and incline (i.e., angle), as shown in Figure 2a, b, and c. Lastly, in the category of *perspective*, the level of *abstraction* depicted by all the students is *macroscopic*. What this analysis indicates is that the majority of the students emphasised the following through their drawings: (a) the *movement* of the roly poly moving to and fro, (b) the *temporal sequence* caused by the application and removal of the force driving the action, (c) the *alignment* of the roly poly between its initial (upright) position and another (horizontal or incline) position, and (d) the *macroscopic* perspective of what they saw. Table 9 shows the distribution of the students' diagrams according to the *movement*, *connective*, *spatial* and *perspective* relationships.

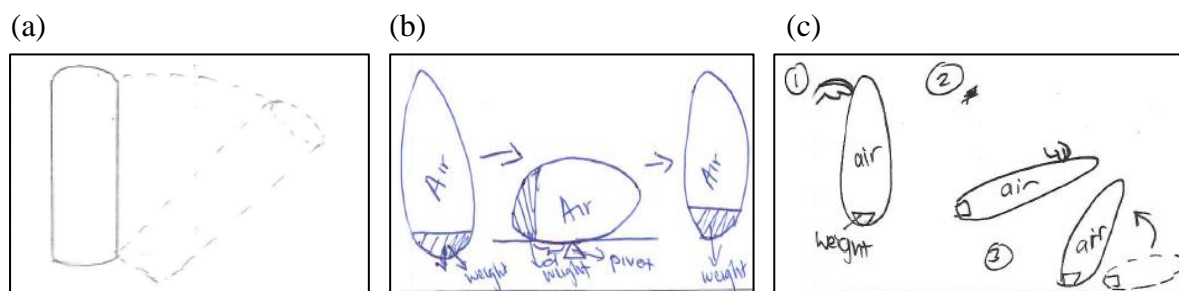


Figure 2. Students' diagrams to show *movement*, *temporal sequence* and *alignment* of roly poly:

- (a) movement using path line, no temporal sequence, angled alignment
- (b) no movement, temporal sequence using arrow, perpendicular alignment
- (c) movement using path line and arrow, temporal sequence using numbering, angled and perpendicular alignment

The students' visual emphasis on *movement*, *temporal sequence*, *alignment* and *macroscopic perspective* is consistent with their initial written explanations. For example, consider the following students' explanation that accompanied the drawing shown in Figure 2c (also shown in Figure 1):

When the roly poly is pushed down and it's parallel to the ground, once the effort is gone, the roly poly will return to its original state.

In a similar way, the written statement emphasised the *movement* ("pushed down", "will return"), *temporal sequence* ("when", "and", "once", "will") and *alignment* ("parallel" and "original state"). Also, consistent with the *macroscopic perspective*, the subjects of the statement only involve concrete objects ("roly poly", "ground") without any abstract

constructs (e.g., moment, centre of gravity). In this particular example shown in Figure 2c, the student also drew a hand (another macroscopic object) adjoining the roly poly, thus signifying the “pushing” and “effort” that is responsible for the *movement* and *alignment* of the roly poly. Although the drawing and written statement are consistent to each other, it is important to note that the overall explanation (written plus visual) does not sufficiently account for *why* the roly poly will return to its original position. This is where the students’ drawings exhibit some gaps in relation to the reference diagram drawn by the teacher.

Table 9. Distribution of physics diagrams according to movement, connective, spatial and perspective relationships

Category	Relationship	Number of diagrams (n=25)
Movement	Arrow, Path, & Wavy	18 (72%)
	No Movement	7 (28%)
Connective-Temporal	Numbering, Arrow, & Ordered Juxtaposition	12 (48%)
	No Temporal Sequence	13 (52%)
Spatial-Alignment	Perpendicular & Angle	21 (84%)
	Parallel	4 (16%)
Perspective-Abstraction	Macroscopic	25 (100%)
	Symbolic	0

Analysis of the reference diagram (reproduced in Figure 3) reveals several contrasting emphasis. First, there is no indication of any movement in the diagram. Second, there is also no explicit indication of a temporal sequence using numbering or arrow to show the passage of time from the upright to horizontal position. Although there is a juxtaposition of two positions (vertical and horizontal) in the diagram, the purpose of this juxtaposition is more for comparing the two positions rather than showing the dynamics of toppling the roly poly. These contrasts show that, in the context of explaining why the roly poly returns to its original position, it is not important to emphasise its movement or any time-bounded sequence. Instead, what accounts for the causal explanation is the shift in position of the roly poly’s centre of gravity in relation to its pivot, and this shift is reflected in the reference diagram, under the analytical categories of *abstraction* and *spatial*.

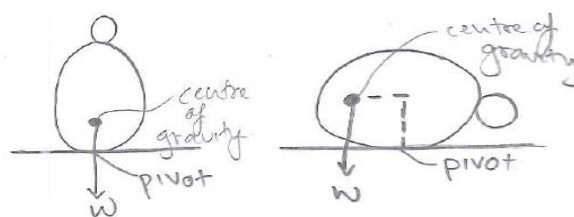


Figure 3. Diagram provided by the teacher

In *abstraction*, there is an abstract level of representation showing the centre of gravity (an imaginary construct) and the force of gravity acting on it (W or weight), both of which are superimposed onto a macroscopic depiction of the outline of the roly poly. This is a major difference from the macroscopic perspective shown in all the students' drawings. Under *spatial*, similar to the students' drawings, there is an emphasis on a perpendicular alignment between the roly poly's vertical and horizontal positions. However, what is different and salient here is also the perpendicular alignment between two abstract lines – the line of action along W and the dotted line (called the moment or lever arm) from the centre of gravity to vertical line joining the pivot (see Figure 3). Showing this perpendicular alignment visually is important in order to account for the cause of the turning effect produced by W in returning the roly poly to its original position. All the students did not draw this aspect, and correspondingly, they also did not mention about the turning effect in their written explanation. Interestingly, the teacher did not highlight the gaps in the students' drawings during and after this lesson.

Illustration of Analysis in Chemistry (with Classroom Discourse)

As a contrast to the physics example, we provide another example taken from a lesson activity on chemical bonding. In the activity, the students were asked to state and explain whether de-ionised water can conduct electricity. The Predict-Observe-Explain (POE) strategy and a worksheet were used for students to write their predictions and initial explanations, with the aid of diagrams that show the molecular structure of de-ionised water in both solid and liquid state (see Figure 4).

2.0 Properties of Covalent Substances (Simple Molecular and Giant Molecular)

Discussion 2

Question A: What do you understand by the term 'de-ionised' water?

ions are removed

Question B: If the solid NaCl is replaced by ice made from pure de-ionised water, do you expect the bulb to light up? How about when it melts?

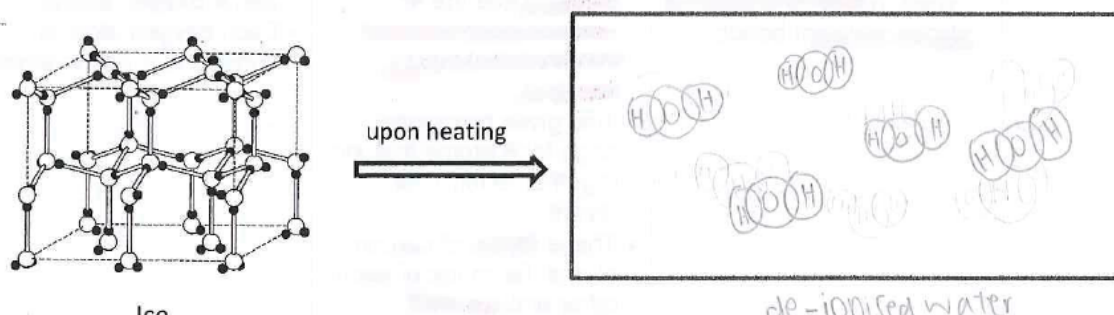


Figure 4. A sample of student's worksheet used in the chemistry lesson

For this analysis, the categories most relevant to the drawing analysis are *association* and *spatial*. Specifically, we focused on two levels of *association* of water molecules in the diagram – between hydrogen and oxygen atoms (intra-molecular) and between water molecules (inter-molecular).

For intra-molecular *association*, we looked at how oxygen (O) atom was linked to two hydrogen (H) atoms. The range of drawings showed three different relationships – *independent*, *intersecting*, and *adjoining*, with each signifying a different intra-molecular bond. A small minority of students (8%) included completely separated hydrogen and oxygen atoms, floating *independently* (Figure 5a). The majority of students (92%) drew intact water molecules with two hydrogen atoms linked to one oxygen atom as either *intersecting* (24%) or *adjoining* (68%). While the difference between these two relationships is subtle, each shows different meaning of H-O bonding in water. The diagram with *intersecting* atoms (Figure 5b) implies the atoms are sharing some space to form a strong bond between H and O. The diagram with *adjoining* atoms (Figure 5c) suggests hydrogens are glued on the surface of oxygen rather than sharing a space.

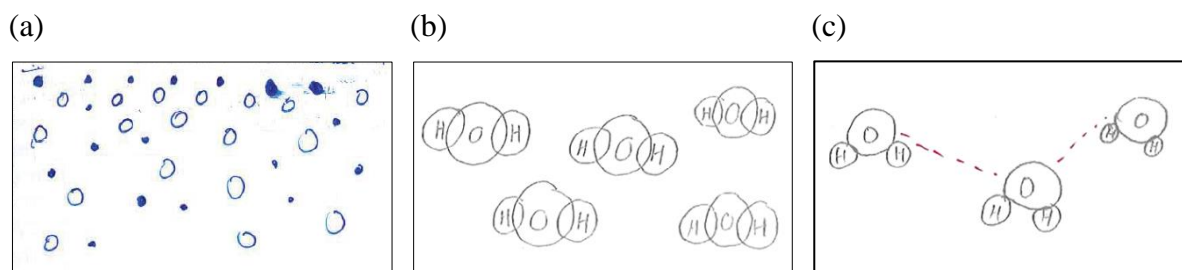


Figure 5. Students' diagrams to show different *associations* of water molecules:
 (a) hydrogen atoms *independent* of oxygen atoms (no water molecules);
 (b) *independent* water molecules with two hydrogen atoms *intersecting* one oxygen atom
 (c) *connecting* water molecules with two hydrogen atoms *adjoining* one oxygen atom.

For inter-molecular *association*, the drawings showed two different relationships – *independent* and *connecting*. About half of students (48%) did not draw any intermolecular associations. Water molecules were floating around *independently*. On the other hand, 44% of the students drew dotted lines to *connect* water molecules as seen in Figure 5c. (Based on video observation, many of the dotted lines were actually added after the teacher drew her diagram; see later excerpt). Table 10 shows the distribution of the students' diagrams according to the *association* relationship that were analysed.

Table 10. Distribution of chemistry diagrams according to *association*

Category	Relationship	Number of diagrams (n=25)
Association:	Independent	2 (8%)
Intra-molecular	Intersecting	6 (24%)
(H-O bonding)	Adjoining	17 (68%)

Association:	Independent	12 (48%)
Inter-molecular	Connecting	11 (44%)
(water-water connection)	No Molecular Depiction	2 (8%)

The above analysis was used to support the interpretation of the occurring classroom discourse. After the students had completed the POE activity, the teacher asked two students to present their drawings to the class (through a document reader). The first student's drawing was similar to Figure 5b while the second student's drawing was similar to Figure 5a. The teacher then used both of their drawings to talk about the different kinds of bonding they needed to understand, as seen from the following excerpt:

Line	Speaker	Utterance & Gesture
1	T	Now, why am I showing you this example? Because I want you to understand that when I melt something, alright, a simple covalent compound are actually. do not break the bond between them
2	T	Alright, so what is it that I am breaking? (<i>9 second wait time</i>). Huh, if you look at the diagram, what is it that I am breaking?
3	T	Let me show you, you have this (<i>drew an enclosing box followed by 1 H₂O inside</i>). Correct or not? So in the solid state, it was all packed packed packed up (<i>gestured with 2 hands to signify molecules inside the enclosing space</i>)
4	T	Then in the liquid state, you showed me this (<i>drew 2 more H₂O's a distance away</i>). At first, they supposed to be close and packed (<i>gestured with 2 hands over molecules to signify together</i>). Closely packed. Then after heating (<i>drew an arrow to the left of the enclosing box</i>), this is what you get. What did you notice about the distance between the molecules? (<i>gestured with 2 hands over molecules to signify separated</i>)
5	S	Further
6	T	They are further apart (<i>drew a dotted line between two H₂O's; See Figure 6</i>).
7	T	So. What kind of bonds are you breaking? (<i>drew a line to the dotted line</i>). Is it a bond? To be very specific, what is it you are overcoming here?
8	S	(softly) Forces of attraction
9	T	The forces of?
10	S	Attraction
11	T	Attraction. Good (<i>Wrote forces of attraction linking to the dotted line</i>)

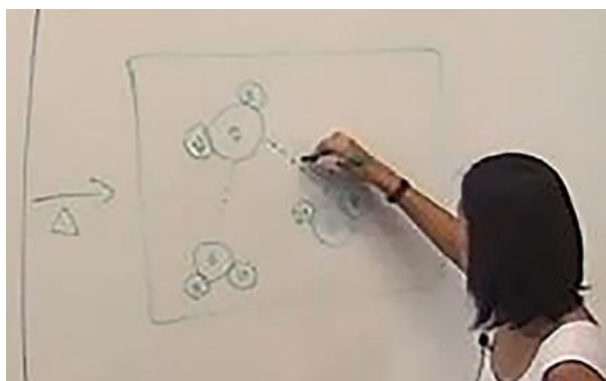


Figure 6. Diagram drawn by the teacher on the whiteboard

In this example, the teacher (T) was implicitly showing three different types of *association* through her drawing: (a) an *adjoining* intra-molecular bond between H and O (line 1), (b) an *independent* inter-molecular relation between H₂O_s (line 2), and (c) a *connecting* inter-molecular attraction between H₂O_s (line 6-11). At the same time, her drawing, utterance and gesture from line 4 to 6 also highlighted the *spacing* in terms of how close or far apart were the H₂O_s, but this is a *spatial* category. Consequently, there was some confusion in line 6 whether the dotted line drew by the teacher signified (a) the distance between two H₂O_s (corresponding to her simultaneous utterance “They are further apart” and previous utterance in line 4) or (b) the force of attraction (corresponding to her simultaneous writing of “forces of attraction” linking to the dotted line and subsequent utterances from line 7 to 11). This confusion was evident from the immediate excerpt, where a pair of students clarified with the teacher on their drawing to represent the force of attraction:

Line	Speaker	Utterance
10	T	What’s this? Which one are you drawing for me?
11	S	I’m trying to (<i>showed her drawing to T</i>)
12	T	Ah, okay. Be very careful because in bold line being used right, they are termed as bonds. So when I draw it, you seem to imply that oxygen to oxygen there is one more bond here. So if you want to show in diagram form
13	S	Dotted line
14	T	Yes, exactly

This excerpt shows the students were initially not clear about how to represent the inter-molecular association between H₂O_s. When they used bold line, the teacher corrected them as the line could be interpreted as a bond instead of a force of attraction (line 12). Subsequently, the students understood they needed to use dotted line instead (line 13). In this case, the teacher only explained the difference between bold and dotted line to denote the nature of association between H₂O_s for these two students. However, she did not make it clear herself in the earlier excerpt on how to explicitly draw the different associations and the difference in using dotted line to represent either distance or force. As such, other students may not see the subtlety in terms of various associative meanings as well as spatial meaning as represented by drawing a line.

Discussion

For the purpose of this paper, the application and usefulness of the analytical framework will be discussed in response to two key questions: (1) What value does the framework add to the analysis? (2) How applicable is the framework across topics, subject areas and research contexts?

Affordance of Analytical Framework

For the first question, we use the examples from moment and chemical bonding to discuss how the analytical framework had supported our analysis and interpretation of the students' drawings. First, the framework provided a comprehensive and hierarchical list of meanings that can be made through a diagram (a total of 48 possible relationships in 7 categories). This allowed us to systematically scan through the range of possible meanings and identify categories that were relevant to the topic being analysed. From the scan, we narrowed the relevant meanings to the identified categories of *movement*, *connective*, *perspective-abstraction*, and *spatial-alignment* for moment and *association* and *spatial-spacing* for chemical bonding.

Each identified category then served to focus our attention to notice subtle features found in the students' diagrams and examine them in terms of the list of relationships provided in the framework. For instance, in the category of *association*, we were able to (a) distil the various ways students indicated the connections within and among water molecules in a liquid state as *independent*, *connecting*, *adjoining*, *intersecting*, or *inclusive* and (b) subsequently focus our interpretation to notice the confusion caused by the dotted line in representing various associative meanings as well as spatial meaning. In this aspect, the framework provided an "interpretive lens" (Cheney, 2000) to notice and make visible phenomena that tend to be subtle or hidden on the surface.

Besides functioning as an interpretive lens, the framework also provided a way for us to codify and categorise the ideas represented in the students' diagrams, and consequently making the observed phenomena possible for pattern recognition and communication between researchers. Because the framework is also a typology of the possible meanings that can be made through a diagram, it can be used as a coding scheme to systematically render the data into distinguishable categories of meaning. The purpose of this coding process is not to generate quantitative analysis and claims, but to facilitate an evidence-based interpretation to discern interesting or recurring patterns among the instances in the data.

Furthermore, the framework also provided a metalanguage for researchers to describe the observed patterns in terms of the meaning-making functions of the diagrams. The New London Group (1996, p. 77) defines metalanguage as a "language for talking about language, images, texts, and meaning-making interactions". As drawing is a form of language, it is useful to have a metalanguage (language about language) that will allow researchers to talk about and communicate the functions of images in our analysis.

Overall, the framework allowed us to describe and make claims about the students' diagrams based on systematic evidence, and thereby identify key features that are important

to understand a particular conceptual situation. For instance, the students' diagrams might appear on the surface to be relevant to the topic being discussed (e.g., molecular arrangement to show chemical bonding, toppling roly poly to illustrate turning effect). However, a deeper analysis aided by the framework has revealed the diagrams were not emphasising the subtle meanings and relationships that are key to representing and explaining the phenomena. In the physics example, the spatial position of its centre of gravity (an abstract entity) was a key feature that was missing in the students' diagrams as they only emphasised the movement and temporal sequence of the roly poly. In the chemistry case, the ambiguity of the dotted line as simultaneously representing distance, bond and force of attraction caused an issue for some students. Thus, the framework was useful in identifying and describing how diagrams are used (or not used) to support key conceptual ideas in science. This identification can also apply to diagrams in textbooks as well.

Applicability of Analytical Framework

In the development of an analytical framework for visual representations, one of the issues often raised is how general and specific is the framework applicable for a range of topics and content areas. A framework that is topic-generic has wider appeal and applicability across more situations as compared to a topic-specific framework, but could be less useful for a more detailed analysis.

The framework that we developed is specific to scientific discourse but generically applicable to most topics and sub-disciplines within the natural sciences. Empirically, we have tested the applicability of the framework based on the data corpus that was available to us, which included a range of topics in physics and chemistry such as dynamics, kinetic model of matter, wave, sound, chemical bonding, redox reaction, and electrolysis. Due to this generalisability, the framework has the potential to provide a unifying analytic scheme to examine the meaning of any drawing (e.g., a line, circle) across various topics. For instance, the five sub-categories of *association* – *independent*, *connecting*, *adjoining*, *intersecting*, or *inclusive* – are applicable whether we are examining the relationships between microscopic objects such as electrons, atoms, molecules or cells, as well as macroscopic objects such as the connections between apparatus, equipment, strings, wires or connecting glass tubes.

In this study, although we do not have examples from biological and earth sciences (due to lack of data in those subject areas), there is no reason to imagine how drawings from those disciplines will be drastically different to the point where the framework is not applicable. Nevertheless, the lack of biology and earth science examples is still a limitation in this study and future research is needed to test and expand the categories and sub-categories in this framework to include a range of topics those areas.

While the relationships and categories in this framework can be applied generically to any topic in science, the interpretation of the specific meaning and significance of a diagram is always context dependent, both the social context in terms of the norms and conventions in the environment (e.g., classroom, subject area) and the local context as determined by what occurred prior to and at the moment the drawing was made. For example, an unbroken or dotted line joining two visual objects would denote some kind of relationship (classified as

connecting association) in any context. However, whether the line signifies distance, an intermolecular force, or an imaginary reference line will depend on a number of contextual information, which the analyst must draw from the available data to inform his/her interpretation. Such contextual information usually involve domain-specific knowledge of the subject matter, curriculum goals, learners' prior knowledge, and the interaction that is occurring. Thus, other data sources besides the students' diagrams, such as written texts, videos or interviews, are often needed to support this interpretation process.

Consequently, it is important to point out that, consistent with the notion of multimodal meaning-making (Lemke, 1998; Tang, 2011), students' drawings (a visual mode) must not be interpreted in isolation from other modes of representation, particularly speech or writing. This is where data from other modes, such as written words, speech and gestures, should be used to support and contextualise the visual analysis. In the examples provided in this paper, we have demonstrated how data from two other sources (e.g., written explanations, classroom discourse) were used to support our interpretation. Both examples also highlighted how various categories and sub-categories from the visual analytical framework were applied in the multimodal analysis with verbal language and gesture.

Implications

The framework developed in this study can potentially benefit science teachers in using representations to support the teaching and learning of science. Research focusing on learning with representations has increasingly emphasised the importance of using student-generated representations to help students reason, explain, and demonstrate their scientific thinking and understanding (Ainsworth et al., 2011). To implement these pedagogical approaches, teachers need to have a clear framework to recognise representational features and meanings made in students' drawings. In this aspect, this analytical framework could serve as a starting point for further development into pedagogical guidelines and interventions.

One possible idea is to develop the framework into a teachers' guide in order to support teachers in getting students to generate and express their ideas through drawings. In science class, student-generated diagrams tend to be descriptive rather than explanatory. To encourage students to draw diagrams as part of their reasoning and problem solving, teachers need to identify key conceptual and representational features, instruct students what to include and how to include them in diagrams, and provide constructive and critical feedback on students' diagrams to improve their understanding. As such, the framework can be used as an interpretive lens for teachers to evaluate the ideas made by the students through their drawings and discern the subtle gaps that students tend to miss in their diagrams, particularly relationships related to association, spatial, movement, and temporal/comparative connective that are crucial to representing scientific phenomena.

The use of this framework as a metalanguage is not exclusive for researchers to facilitate their communication, but it is also applicable for teachers and students to explicitly describe their drawings and discuss the underlying ideas represented in their drawings during class. For instance, students can use the metalanguage of *association* (as *connecting*,

adjoining, inclusive etc.) to communicate explicitly how their visual objects are connected to one another and explain what those connections represent. Doing so will help teachers and students pay attention to the multifaceted meanings of their drawing more methodically. Current research is looking into the development of a metalanguage that will assist teachers and students to describe the characteristic of drawings and other images as embedded within scientific experiments, explanations and arguments (Tang, 2019).

Another possibility is to extend the framework into an assessment rubric for teachers and students to evaluate the diagrams in relation to key ideas of specific topics. This can be used both as a formative assessment for students to reflect and continually improve their drawings with the aid of a metalanguage that was discussed earlier, as well as a summative assessment to evaluate the range of relationships that were represented through their drawings. In chemical bonding for example, we learned from the analysis that *association* and *spatial* relationships are crucial to represent visually the characteristics and behaviours of atoms and molecules. Therefore, through the rubric, teachers can direct students' attention to those key components: (a) the relationships between atom-atom, atom-molecule, and molecule-molecule and (b) their spatial dimension, spacing, alignment and distribution in a liquid state, and consequently how to represent these ideas visually. It is important to point out that the purpose of the rubric is not to have students learn and reproduce a narrow and standardised way of drawing these relationships. Some students could create alternative way of representing the same relationships, as long as the reasoning for the representation is explained and justified. Instead, the purpose of the rubric is to direct the students' attention toward how to harness drawing as an important resource (besides verbal language) to facilitate their scientific reasoning.

Much research is still needed to turn these two prospects into pedagogical reality, and to advance this research further, what is needed currently is an analytical framework such as the one presented in this paper.

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