Dagher, Z. R., & Erduran, S. (2013). Laws and Explanations in Biology and Chemistry: Philosophical Perspectives and Educational Implications. In M. R. Matthews (Ed.), *International Handbook of Research in History, Philosophy and Science Teaching* (pp. 1203-1233). Springer, Dordrecht. https://doi.org/10.1007/978-94-007-7654-8_37

Peer reviewed version

Link to published version (if available):
10.1007/978-94-007-7654-8_37

Link to publication record in Explore Bristol Research
PDF-document

Science & Education

Laws and Explanations in Biology and Chemistry: Philosophical Perspectives and Educational Implications

--Manuscript Draft--

Manuscript Number:	SCED922R5
Full Title:	Laws and Explanations in Biology and Chemistry: Philosophical Perspectives and Educational Implications
Article Type:	Handbook
Keywords:	Philosophy of biology, philosophy of chemistry, laws, explanations, science education
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Laws and Explanations in Biology and Chemistry: Philosophical Perspectives and Educational Implications[1]

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Abstract This chapter utilises scholarship in philosophy of biology and philosophy of chemistry to produce meaningful implications for biology and chemistry education. The primary purpose for studying philosophical literature is to identify different perspectives on the nature of laws and explanations within these disciplines. The goal is not to resolve on-going debates about the nature of laws and explanations but to consider their multiple forms and purposes in ways that promote deep and practical understanding of biological and chemical knowledge in educational contexts. Most studies on the nature of science in science education tend to focus on general features of scientific knowledge and under-emphasise disciplinary nuances. The authors aims to contribute to science education research by focusing on the characterisations of laws and explanations in biology and chemistry in the philosophical literature, and illustrating how the typical coverage of biology and chemistry textbooks does not problematise meta-perspectives on the nature of laws and explanations. The chapter concludes with suggestions for making science teaching, learning, and curriculum more inclusive of the epistemological dimensions of biology and chemistry.

1 Introduction

The teaching of history and philosophy of science (HPS) in science education has been advocated for several decades[2]. In recent years, however, there has been increasing interest in the philosophical examination of biology and chemistry as distinct branches of science that differ epistemically from physics in significant ways. Philosophers of biology (Hull 1973, Mayr 2004, Ruse 1988) and philosophers of chemistry (Bhushan & Rosenfeld 2000, van Brakel 2000, Scerri & McIntyre 1997) have offered insights into the epistemologies of biology and chemistry. However these insights have not been integrated sufficiently into biology and chemistry education research, curriculum materials, and classroom practice. Research on the nature of science in science education could benefit from such insights in order to improve understanding of not only the disciplinary knowledge but also the meta-level characterisations of scientific knowledge at large.

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[1] An earlier version of this paper was presented at the 2011 IHPST conference and published in F. Seroglou, V. Koulountzos, & A. Siatras (Eds), *Science & culture: Promise, challenge and demand.* Proceedings for the 11th International IHPST and 6th Greek History, Philosophy and Science Teaching Joint Conference. 1-5 July 2011, Thessaloniki, Greece: Epikentro.

[2] See for example Duschl 1990, Hodson 1988, Matthews 1994, and Schwab 1958 & 1978.

As science educators we are concerned with the question of how philosophical insights into scientific knowledge can inform science teaching and learning. The goal is not to contribute to the debates in the philosophy of biology and chemistry, but rather to draw out some aspects of these debates that are relevant for education in light of evidence from empirical studies in science education (e.g. Dagher & Cossman 1992, Erduran & Jimenez-Aleixandre 2008, Sandoval & Millwood 2005). In doing so, we problematise the current state of under utilisation of the epistemological aspects of disciplinary knowledge in science education, and illustrate with examples how it can be practically addressed. It is hoped that the discussion will assist other science education researchers in exploring the philosophical literature for clarifying and justifying educational goals that relate to scientific knowledge claims.

According to Irzik and Nola (this handbook), science can be perceived as a cognitive-epistemic system and as a social system. Scientific knowledge, which constitutes one component of the cognitive-epistemic system, is the culmination of scientific inquiry and includes laws, theories, and models. Focusing on these structural elements in the context of any single discipline would be necessary to understand the nature of that discipline. Among these elements, explanations and particularly laws have been understudied from an epistemological perspective in science education research. For instance, while there is a substantial body of literature broadly on models (e.g. Justi 2000), the study of the particular epistemological aspects of models has been scarce (e.g. Adúriz-Bravo 2012, Adúriz-Bravo & Galagovsky 2001, Erduran & Duschl 2004). Similarly, despite the importance of laws and explanations in the science disciplines, relevance of their epistemic nature to educational practice is seldom explored (e.g. McComas 2003, Sandoval & Reiser 2004).

One often-cited misunderstanding of the nature of science (NOS) concerns scientific laws. Classified as the number one NOS myth by McComas (1998), many individuals tend to believe "that with increased evidence there is a developmental sequence through which scientific ideas pass on their way to final acceptance as mature laws" (p. 54). Involved in this belief is the thought that science starts out with facts, progresses to hypotheses, then theories, then when confirmed, to laws. Another myth pertains to the idea that scientific laws are absolute (McComas 1998). These beliefs represent only two of many other misunderstandings about the nature of scientific knowledge and pose challenges regarding the best approach to deconstruct them. Several approaches have been proposed for countering these and other nature of science misconceptions (Clough 1994, Khishfe & Abd-El-Khalick 2002, Schwartz et al. 2004), but it remains unclear whether efforts to enhance student understandings of the nature of science have resulted in significant or lasting improvements (Lederman 2007).

The context of laws provides a crucial and relevant nexus for promoting the epistemological aspects of biology and chemistry in the classroom. Focusing on the nature of laws in biology education, for example, serves not only to clear existing misconceptions (as the ones mentioned earlier) but offers insight into basic metaphysical and ontological aspects of the discipline which can enhance student understanding of the subject. The inclusion of 'laws' in chemistry education not only elaborates on this important philosophical thesis but also offers some insight into how students' interest in philosophical aspects of chemistry might be stimulated. Scientific explanations on the other hand refer often to how and why something happens (Chinn & Brown 2000). Typically scientists explain phenomena by determining how and why they occur along with the conditions surrounding the observed events (Nagel 1961). Explanations are important components of scientific theories. They are the backbone of scientific claims, and are consequently a central target for epistemological disputes. It is through the refutation or support of components of scientific explanations that the fabric of theories is woven. In science education, considerable emphasis is placed on developing students' ability to substantiate their explanations using reasons and evidence.

Despite the separation of laws and explanations for contrast in biology and chemistry in this chapter for educational purposes, the distinction of these concepts in the history of philosophy of science is not straightforward. For example, the covering laws in Hempel's positivistic framework function not only as core explanatory components (*explanans*) but also as the targets of explanation (*explananda*). In more recent work, law-like regularities among properties are considered to be a kind of explanation in their own right. For instance, Bird (1998) calls them "nomic explanations". He argues that inferring a law from observation is a form of *inference to the best explanation* (IBE), a common form of scientific reasoning.

The task in this paper is not to articulate the distinctions between laws and explanations from a philosophical perspective. Indeed, as educators, it is beyond the scope of our engagement in philosophy of science to contribute to or resolve existing debates or to generate new knowledge in the field. This task is left to the professional philosophers. Rather, the purpose of this analysis is to draw out some themes around laws and explanations, discussed in philosophy of biology and philosophy of chemistry, in ways that are relevant for science education. For example, Mendel's laws and the Periodic Law are chosen as examples because of their prominence in science curricula at secondary school level, which is our primary area of interest. At times, the discussion will refer to some contentious characterisations of laws and explanations. Again, here the discussion is reflecting ongoing debates to inform the science education community of the sorts of issues that are of concern to philosophers of science. The implications for science education could include problematizing the nature of laws, explanations or indeed the contrast itself. However, given the typically separate reference to laws and explanations in the science curricula, the goal in this chapter is to interrogate the existing literatures for particular and explicit references to either laws or explanations thus informing subsequent analysis of how they are depicted in science education.

Furthermore, while discussions of NOS in the science education literature typically focus on the relationship between laws and theories (specifically on how they are different), they tend to neglect the conceptual disciplinary-based features that pertain to them. Shifting the discussion in this paper from laws and theories to laws and explanations underscores the following key ideas/assumptions: 1) Explanation is a key purpose of science. Theories are developed not as ends in themselves but as powerful explanatory and predictive tools, 2) Laws express regularities that can serve predictive and/or explanatory functions, 3) Explanations are building blocks of scientific theories that can be explored pedagogically at multiple organisational levels, and 4) Explanations are pragmatic and contextual (de Regt 2011).

Focusing on explanations rather than theories in this paper, allows for a nuanced and contextual discussion of their characteristics across disciplines and sub-disciplines from philosophical and educational perspectives. The significance of explanations in science curriculum and instruction is recognised by science educators in a variety of ways. In some cases, concern is expressed about linguistic and epistemic aspects, as with Horwood's (1988) illustration of the lack of consistency between the terms 'explain' and 'describe' in teaching materials and Jungwirth's (1979) findings that high school students tend to equate anthropomorphic and teleological explanations with causal explanations. At the level of instruction, teachers are reported to use a wide range of explanatory types some of which are scientific and some are not, calling for further examination of the appropriateness of these explanations (Dagher & Cossman 1992). More recent work presents evidence for the difficulties experienced by students in generating and justifying scientific explanations (Sandoval & Millwood 2005). In addition, there have been ongoing efforts focused on designing instructional models for supporting student development of scientific explanations (Land & Zembal-Saul 2003, McNeill et al. 2006, McNeill & Krajcik 2012).

In summary, the purpose of this chapter is to discuss characterisations of laws and explanations in biology and chemistry, and extract some implications for teaching, learning, and curriculum. The goal is to demonstrate how some of the ongoing debates about the nature of laws and explanations in biology and chemistry can have useful contributions to teaching these disciplines without necessarily resolving these debates. Exploring the arguments in these debates allows the articulation of how laws and explanations as products of scientific knowledge might be addressed more meaningfully in educational settings by discussing current coverage of laws and explanations in typical biology and chemistry textbooks. The chapter concludes with recommendations for revising textbooks and instruction in ways that restore the grounding of subject matter knowledge in its epistemological context.

2 The Nature of Laws and Explanations in Science

Volumes have been written about the nature of laws and explanations in science, mostly using physics as a basis for analysis. Views about the purpose and nature of these entities have changed over time and some aspects of them continue to undergo some debate. Attempting to summarise this vast literature or represent the diversity of views in few paragraphs is impossible without doing grave injustice to the field. It is necessary, however, to highlight key ideas before discussing the characteristics of laws and explanations in biology and chemistry with the understanding that this brief overview is not exhaustive or representative of extant viewpoints.

What distinguishes a law of nature from any other regularity? Traditional definitions of a scientific law typically refer to "a true, absolute and unchanging relationship among interacting elements" (Dhar & Guiliani 2010, p. 7). This traditional view has been challenged on several bases. Lange (2005) argues that the condition of truth alone does not help make this distinction since other regularities are true also. He proposes the following four criteria to aid in distinguishing laws of nature from other regularities: necessity, counterfactuals, explanatory power, and inductive confirmations. Mahner & Bunge (1997) have argued that laws are said to be "spatially and temporally boundless", where other laws may be "bounded in space and time". Cartwright's critique of "the limited scope of applicability of physical laws" (Ruphy 2003) problematizes the "truth" aspect of laws. Giere (1999) on the other hand holds the view that what has come to be known as 'laws of nature' are in fact historical fossils, holdovers from conceptualisations first proposed in the Enlightenment. He proposes the consideration of models, which he argues are more reflective of how science is actually *practiced*.

The significance of the debates about the nature of scientific laws becomes most relevant when discussing the role they play in supporting explanations in the specific sciences. Attempting a balanced description of scientific laws is a complex undertaking considering debates among philosophers about criteria invoked to distinguish between various types of laws such as strict versus *ceteris paribus* laws, empirical versus *a priori* laws. Such criteria include mathematical models, necessity, and explanatory and predictive potential. Some of these debates will be revisited in the context of the specific sciences later in this chapter.

In an insightful paper written more than five decades ago, Bunge (1961) classified lawlike statements from various philosophical standpoints into more than seven-dozen kinds. He concluded his detailed analysis with calling for less stringent philosophical restrictions regarding what could be classified as a law:

> There are as many classifications of law statements as viewpoints can be profitably adopted in their regard, and there seems to be no reason—save certain philosophical traditions—why most law statements should be regarded as nonlaw statements merely because they fail to comply with either certainty, or strict universality, or causality, or simplicity, or any other requisite found necessary in the past, where science seemed to concern itself exclusively…. That lawlike (*a posteriori* and general in some respect) statements be required corroboration and systematicity in order to be ranked as law statements, seems to fit contemporary usage in the sciences. (Bunge 1961, p. 281).

Bunge's pragmatic view regarding what constitutes scientific laws is a profound one. Continued debates about what counts as a scientific law, argued with core propositions of particular science disciplines, seem to be fundamentally grounded in normative or pragmatic standpoints and from this perspective cannot said to have been fully resolved. Perhaps the most valuable context for such debates has been relative to the role of laws in generating or supporting scientific explanations (Press 2009).

Explanation is often hailed as one of the main goals of the scientific enterprise. Nagel (1961) articulates the central role of explanations in science when he states: "It is the desire for explanations which are at once systematic and controllable by factual evidence that generates science; and it is the classification and organisation of knowledge on the basis of explanatory principles that is the distinctive goal of the sciences." (p. 4). While this stance towards explanation may seem obvious, it does not represent a united or a longstanding view. Logical positivists for instance, led by Ernest Mach, held that the aim of science is not to explain but rather to describe and predict phenomena (de Regt 2011). Discussions of the components that distinguish scientific explanation from other forms of explanation have spurred significant philosophical debate and led to a variety of accounts that have expanded understanding of their diversity.

The following discussion focuses on describing three main families or models of explanation. These are: nomological explanation, causal explanation, and functional explanation. According to de Regt (2011), these models are not mutually exclusive but can be used to explain the same phenomenon or explain phenomena in different disciplines.

The Deductive-Nomological (D-N) or Covering Law model of explanation proposed by Hempel and Oppenheim (1948) frames explanation as a logical argument in which the conclusion, or *explanandum* follows from a set of premises, or *explanans.* The premises that constitute the *explanans* have to include at least one general law and other relevant preconditions. The general law in Hempel's account is a key component of the explanation process and has to be a "true universal generalization", allowing for the explanation and/or prediction of various events. One of the unresolved issues in the D-N model of explanation, pointed out by de Regt (2011), is that science is usually concerned with the explanation of laws, which necessitates the use of other more general laws. This proves to be problematic without "giving an adequate criterion for the generality of laws" (p. 159). One derivative of nomological explanation is the inductive-statistical explanation (I-S), in which the law used in the *explanans* contains high probability that subsequently gives rise to an inductive (as opposed to deductive) support to the *explanandum.*

The Causal Mechanical (CM) model of explanation moves away from the conception of explanation as an argument (Salmon 1984). In generating this model, Salmon abandoned the attempt to characterise explanation or causal relationships in purely statistical terms. The CM model employs several central ideas. A causal process is a physical process, like the movement of a ball through space, that is characterised by the ability to transmit a mark in a continuous way. A mark is some local modification to the structure of a process. A process is capable of transmitting a mark if, once the mark is introduced at one spatio-temporal location, it will persist to other spatio-temporal locations even in the absence of any further interaction.

Causal processes contrast with pseudo-processes that lack the ability to transmit marks. An example is the shadow of a moving physical object. The other major element in Salmon's model is the notion of a *causal interaction.* A casual interaction involves a spatio-temporal intersection between two causal processes which modifies the structure of both—each process comes to have features it would not have had in the absence of the interaction. A collision between two cars that dents both is a paradigmatic causal interaction. According to the CM model, an explanation of some event *E* will trace the causal processes and interactions leading up to *E* (Salmon calls this the *etiological* aspect of the explanation), or at least some portion of these, as well as describing the processes and interactions that make up the event itself (the *constitutive* aspect of explanation). In this way, the explanation shows how *E* "fit[s] into a causal nexus" (Salmon 1984, p. 9).

Functional explanations typically account "for the role or presence of a component item by citing its function in the system". This type of explanation is commonly employed in the life and social sciences because these domains typically deal with "complex organized systems, the components of which contribute to the working of the system (organisms, human minds, societies and so forth)" (de Regt 2011, p. 164). Achinstein (1983) presents three categories of functional explanations: The good-consequence doctrine in which the function confers some good on something or someone, the goal doctrine in which the function contributed to a goal that something, its designer, or its user has, and the explanation doctrine in which the function includes causes or reasons or consequences. These categories probably make it easier to differentiate between functional explanations with teleological goal-oriented tendencies (the second doctrine) and other functional explanations. Achinstein further distinguishes between three types of functions: design functions, use-functions, and service-functions, allowing for a more nuanced and contextual differentiation between different functional explanations.

Philosophers of science have discussed a plethora of explanation models[3]. Additional contributions have came from philosophers of biology (e.g. Rosenberg & McShea, 2008, Schaffner, 1993, Sober 2008) and philosophers of chemistry (e.g. Goodwin 2008, Scerri & McIntyre 1997, van Brakel 2000) presenting and defending explanatory models that communicate the uniqueness of their disciplines. The following section describes the characteristics of laws and explanations in biology and chemistry focusing on aspects that have direct implications for science education.

3 The Nature of Laws and Explanations in Biology and Chemistry

3.1 Laws in Biology

There has been considerable discussion among philosophers regarding the appropriateness or meaningfulness of the concept of law in biology. Mayr takes the stance that "laws play a rather small role in theory construction in biology". He attributes this "to the greater role played in biological systems by chance and randomness. Other reasons for the small role of laws in biology are the uniqueness of a high percentage of phenomena in living systems as well as the historical nature of events" (Mayr 2004, p. 28). The fact that biological systems are governed by "dual causation" imposed by natural laws and by "genetic programs" makes the theories that explain them distinct from those pertaining to physical systems. (Mayr 2004, p. 30). For Mayr, the matter is not one of nomenclature but one of substance. He concedes that even though some of the important concepts in biology "can be phrased as laws, they are something entirely different from the Newtonian natural laws" (Mayr 2004, p. 30).

Garvey (2007) takes a position similar to Mayr's when he states that "Biology does not have strict mathematical laws of its own. There are, as in any science, generalisations. But these generalisations have a habit of proving to be: (i) not distinctive to biology; (ii) not strict, exceptionless, mathematical laws; or (iii) not laws at all. Put in more positive terms, the generalisations found in biology are: (i) laws that belong to other sciences, (ii) *ceteris paribus* laws[4]; or (iii) true by definition." (p. 157-158). Others such as Uzman (2006) maintain that some biological observations tend to be presented as theories at a time when they should be considered laws of nature. He identifies four laws: The First law: all phenomena of life are consistent with the laws of chemistry and physics; Second law: The cell is the fundamental unit of life. Third law: Life is continuous across generations. Fourth law: Life evolves – populations change genetically and irreversibly through time. Örstan (2007) attributes to E. O. Wilson the claim that biology has 2 main fundamental laws: "1. All of the phenomena of biology are ultimately obedient to the laws of physics and chemistry, and 2. All of the phenomena of biology have arisen by evolution

[3] For example see Giere (1988), Harré (1988), Hesse (1970), Pitt (1988), Salmon (1987), and Scriven (1970).
[4] The Latin *ceteris paribus* stands for "all things being equal": *ceteris paribus* laws are laws that have exceptions, often contrasted with strict or 'real' laws (Garvey 2007).

thru[sic] natural selection." It can be argued, using Garvey's criteria, that even these 'laws' constitute generalisations that are non-mathematical and/or true by definition.

Reasons advanced in support or opposition to the concept of laws in biology can be found in various sub-disciplines (evolutionary biology; systems biology; molecular biology; ecology). While the complexity of biological systems is widely acknowledged, constant efforts are being undertaken to establish fundamental biological organising principles that exhibit lawlikeness. For example, Dhar and Guiliani (2010) present an approach for uncovering fundamental organising principles in systems biology. Dodds (2009) has identified 36 laws in ecology to minimise the perceived complexity in interpreting ecological systems. McShea and Brandon (2010) recently proposed a detailed account for a "Zero Force" evolutionary law that they believe to be to biology what Newton's first law is to physics. These efforts demonstrate that the complexity and contingencies inherent in biological systems have not discouraged biologists and philosophers of biology from trying different approaches to generating "fundamental organising principles."

To attain the ideal status of a universal law, Dhar and Guiliani (2010) believe that what biologists need to do but is difficult to attain, is to construct generalisations that connect all levels from atoms to ecosystems. From their perspective, Mendel's Laws provide a reasonable framework at the phenotypic level, but an equivalent framework is absent at the cell-cell level. They believe, however, that just because this framework is currently absent does not mean it is not attainable in principle. Thus they are optimistic about the possibility of finding powerful generalisations at the different levels of organisation (Dhar & Guiliani 2010) or developing empirical biological laws (Elgin 2006). In Elgin's (2006) view, a "distinctively biological law" is one in which "two conditions must be met: (1) all non-biological concepts in it must be mathematical, (2) It must contain at least some biological concepts and these concepts must be essential to its truth" (Elgin 2006, p. 130).

Other philosophers of biology take a pragmatic approach that "replaces a definitional norm with an account of the *use* of scientific laws." (Mitchell 2000, p. 259). From Mitchell's perspective, "the requirements for lawfulness fail to reflect the reality of scientific practice. As a consequence, the traditional understanding of laws is incomplete and fails to account for how humans have knowledge of the complexity of the world." (Mitchell 2009, p. 53). Mitchell characterises the reasons used to deny the existence of laws in biology as rooted in a normative orientation that regard laws along the Popperian tradition: "bold, universal, exceptionless". (Mitchell 1997, p. S473). Arguing against the privileging of a very special type of generalisation that meets very stringent conditions and occurs very rarely even in physics, she affirms that "the contingency of generalizations in biology or other sciences does not preclude their functioning as 'laws'-- generalizations that ground and inform expectations in a variety of contexts" (Mitchell 1997, p. S478).

Mendel's laws of segregation and independent assortment are popular topics for debating the nature of biological laws. Briefly stated,

> Mendel's first law, the Law of Segregation, states that while an organism may contain a pair of contrasting alleles, e.g. Tt, these will segregate (separate) during the formation of gametes, so that only one will be present in a single gamete, i.e. T or t (but not both or neither). Mendel's second law, the Law of Independent

> Assortment, states that the segregation of alleles for one character is completely random with respect to the segregation of alleles for other characters. (Dictionary of Botany 2003).

However, neither their highly contingent nature (Mitchell 2009) nor the historical ambiguity surrounding their ascendance from principles to laws (see Footnote 2 and Marks 2008) are adequate reasons for demoting them to accidental generalisations. Rather than deny the existence of biological laws, it is more useful in the context of the variation inherent in biological systems to provide "a better understanding of contingency so that we can state the many ways in which laws are not always 'universal and exceptionless'" (Mitchell 2009, p. 63).

3.1.1 The Case of Mendel's Laws in Biology Textbooks

Mendel's laws of segregation and independent assortment are often described in biology textbooks to various levels of detail with some reference to Mendel's profile and pea-plant experiments. Inheritance is a classic topic in middle and high school biology curriculum materials. A typical chapter in one high school biology book (BSCS 2003) begins with getting students to consider similarities of features between members of different generations in families. Starting with discussions about familiar experiences the chapter invites students to read the tragic case of hemophilia in the family of the last Czars, then leads them to work on different scenarios in order to predict inheritance patterns. Next, students are engaged in simulations, using beans, to help them understand the inheritance of one and two traits. The chapter explores inherited patterns, defines gametes, describes meiosis, tracks genes and chromosomes through meiosis by guiding students to construct a physical representation that tracks the genotype of the newly divided "cells" and addresses the role of sample size in leading to more accurate predictions. Next the book introduces Gregor Mendel and a video segment that provides data for students to use to make predictions then compare their predictions with actual results provided by the teacher. Additional exercises pertaining to linked and sex-linked traits are offered to deepen and elaborate the concepts before the chapter ends with a discussion of the genetic basis for human variation.

Of particular interest to this paper is the book's reference to Mendel's second law. The following excerpt represents one of two occasions in which it is mentioned in one chapter: "When you follow the inheritance of 2 traits (a di-hybrid cross), more complex patterns result. In garden peas, the genes for the traits of pod color and pod shape are on different chromosomes. As a result, their inheritance conforms to Mendel's law of independent assortment." (BSCS 2003, p. 438). The only other significant reference to this law appears later in the book in an essay at the end of the unit. The essay discusses the concepts of phenotype and genotype, and concludes with an example that demonstrates the random inheritance of traits demonstrating how a baby rabbit may inherit different genes for particular traits from the father and mother like fur color and eye color independently of each other. The essay concludes with the following historical narrative:

> The principle of independent assortment was discovered more than 150 years ago in a small European monastery garden. A scholarly monk named Gregor Mendel used pea plants to study patterns of inheritance. Mendel experimented with many generations of pea plants. His insights alter became the cornerstone for explaining basic patterns of inheritance. (BSCS 2003, p. 499)

As seen in these excerpts, the same concept is referred to as a law in one section of the book and as principle in another. It is not clear whether the shift in language is accidental or whether it refers to the historical evolution of this idea from 'principle' at the time of its inception to 'law' in later references to this idea[5]. While inconsistency in how textbook authors use categorisations of scientific knowledge has been already documented (e.g. McComas 2003), noting this inconsistency in this paper underscores what appears to be confusion or lack of clarity about the purpose that this law/principle serves, as demonstrated in both excerpts. The textbook provides no further details about what the 'law' or 'principle' of independent assortment entails or the role it plays in explaining phenomena. It is stated casually as a claim that explains some observations, no different than another claim in terms of its generalisability (or lack thereof), or ability to explain or predict. It is not made explicitly clear that this generalisation can be used to explain or predict phenotypes and genotypes of new generations of siblings that go beyond the specifics of the examples discussed in the chapter.

The main issues in the examples quoted earlier are: 1) the striking lack of clarification about what a law entails, 2) the unexplained switch from 'law' in the chapter to 'principle' in the historical anecdote, 3) lack of explicit reference to the relative strong explanatory power (Woodward 2001) expressed that is qualitatively and quantitatively different from other concepts presented in the textbook.

In another high school biology book (SEPUP 2010), the discussion of Mendel's work is devoid of references to laws or principles. Some 60 pages after describing the historical work of Mendel, and only in the context of discussing genes and chromosomes, there is a brief reference to one of Mendel's laws:

> When the chromosomes line up before division, the paternal and maternal chromosomes in the pair line up randomly and separate independently of each other. This is called independent segregation of the chromosomes. Independent segregation of chromosomes explains the behavior of genes that follow Mendel's law of independent assortment. It also accounts for the fact that genes that are linked on the same chromosome don't follow the law of independent assortment…. (SEPUP 2010, p. 356).

This passage illustrates how Mendel's law of independent assortment exerts an explanatory function. But it is the only place other than the "Glossary" section at the end of the book, where this law is mentioned. The apparent retreat from explicit emphasis on Mendel's laws in both textbooks either reflects a general trend of accidental nature, or an outcome of authors' awareness of the philosophical controversy about laws in biology. In both cases, avoidance of

[5] In his review of early textbooks, Marks (2008) notes that initially, Mendel's law was often presented in the singular in contrast to Galton's Law of Ancestral Heredity as evident in Punnett's 1905 textbook and most other genetics textbooks of the first generation. In his 1909 book, Bateson contrasted Galton's Law against the Mendelian "'scheme', 'principles', 'phenomena', 'methods', 'analysis', 'facts'". (Marks 2008, p. 250). First references to Mendel's Law of Segregation and Law of Independent Assortment appeared in Morgan's second book in 1916, and were further detailed in his 1919 book *The Physical Basis of Heredity.*

explication of the significance of laws or principles in biology in the context of a specific content, such as the one explored here, reduces the likelihood that students will understand the usefulness of this aspect of scientific knowledge relative to its explanatory function. One way to rectify this matter is by using language consistently in textbooks, clarifying what the referents mean, and educating teachers about the distinctive nature of laws in biology, noting their relevance to explaining observations and predicting new ones. Alternatively, teachers can problematize terms like 'laws' and 'principles' and guide the students into a discussion that addresses their meaning and significance.

3.2 Laws in Chemistry

Until fairly recently, the status of laws in chemistry has received little attention within philosophy of science (e.g. Cartwright 1983). With the upsurge of philosophy of chemistry in the 1990s, there has been more focus on what might (or not) make laws distinctly chemical in nature. Some philosophers of chemistry (e.g. Christie & Christie 2000) as well as chemical educators (e.g. Erduran 2007) have argued that there are particular aspects of laws in chemistry that differentiate them from laws in other branches of science with implications for teaching and learning in the science classroom. A topic of particular centrality and relevance for chemical education is the notion of "Periodic Law" which is typically uncharacterised as such:

> Too often, at least in the English speaking countries, Mendeleev's work is presented in terms of the Periodic Table, and little or no mention is made of the periodic law. This leads too easily to the view (a false view, we would submit), that the Periodic Table is a sort of taxonomic scheme: a scheme that was very useful for nineteenth century chemists, but had no theoretical grounding until quantum mechanics, and notions of electronic structure came along. (Christie & Christie 2003, p. 170)

A 'law' is typically defined as ''a regularity that holds throughout the universe at all places and at all times'' (Salmon et al. 1992). Some laws in chemistry like the Avogadro's Law (i.e. Equal volumes of gases under identical temperature and pressure conditions will contain equal numbers of particles) are quantitative in nature whilst others are not. For example, laws of stoichiometry are quantitative in nature and count as laws in a strong sense. Others rely more on approximations and are difficult to specify in an algebraic fashion. As a key contributor to philosophy of chemistry, Eric Scerri (2000a) takes the position that some laws of chemistry are fundamentally different from laws in physics (Scerri 2000a). Whilst the emphasis in physics is on mathematisation, some chemistry laws take on an approximate nature:

> The periodic law of the elements, for example, differs from typical laws in physics in that the recurrence of elements after certain intervals is only approximate. In addition, the repeat period varies as one progresses through the periodic system. These features do not render the periodic law any less lawlike, but they do suggest that the nature of laws may differ from one area of science to another. (Scerri 2000a, p. 523)

Viewed from the perspective of physics, the status of the periodic system may appear to be far from law-like (Scerri & McIntyre 1997). Significantly, the periodic law seems not to be exact in the same sense as are laws of physics, for instance Newton's laws of motion. Loosely expressed, the Periodic Law states that there exists a periodicity in the properties of the elements governed by certain intervals within their sequence arranged according to their atomic numbers. The crucial feature which distinguishes this form of 'law' from those found in physics is that chemical periodicity is approximate. For example, the elements sodium and potassium represent a repetition of the element lithium, which lies at the head of group I of the periodic table, but these three elements are not identical. Indeed, a vast amount of chemical knowledge is gathered by studying patterns of variation that occur within vertical columns or groups in the periodic table. Predictions which are made from the so called periodic law do not follow deductively from a theory in the same way in which idealised predictions flow almost inevitably from physical laws, together with the assumption of certain initial conditions.

Scerri further contrasts the nature of laws in physics such as Newton's Laws of Gravitation. Even though both the Periodic Law and Newton's Laws of Gravitation have had success in terms of their predictive power, the Periodic Law is not axiomatised in mathematical terms in the way that Newton's Laws are. Part of the difference has to do with what concerns chemists versus physicists. Chemists are interested in documenting some of the trends in the chemical properties of elements in the periodic system that cannot be predicted even from accounts that are available through contributions of quantum mechanics to chemistry. Christie and Christie (2000), on the other hand, argue that the laws of chemistry are fundamentally different from the laws of physics because they describe fundamentally different kinds of physical systems. For instance, Newton's Laws described above are strict statements about the world, which are universally true. However the Periodic Law consists of many exceptions in terms of the regularities demonstrated in the properties and behaviours of elements. Yet, for the chemist there is a certain idealisation about how, for the most part, elements will behave under particular conditions. In contrast to Scerri (2000a) and Christie and Christie (2000), Vihalemm (2003) argues that all laws need to be treated homogeneously because all laws are idealisations regardless of whether or not they can be axiomatised. van Brakel further questions the assumptions about the criteria for establishing 'laws':

> If one applies "strict" criteria, there are no chemical laws. That much is obvious. The standard assumption has been that there are strict laws in physics, but that assumption is possibly mistaken . . . Perhaps chemistry may yet provide a more realistic illustration of an empirical science than physics has hitherto done. (van Brakel 1999, p. 141).

Christie and Christie (2000) indicate that taking physics as a paradigmatic science, philosophers have established a set of criteria for a "law statement", which "had to be a proposition that (1) was universally quantified, (2) was true, (3) was contingent, and (4) contained only non-local empirical predicates" (p. 35). These authors further argue that such a physics-based account is too narrow and apply only to simple systems. More complex empirical sciences do not necessarily conform to such accounts of laws:

> The peculiar character of chemical laws and theories is not specific to chemistry. Interesting parallels may be found with laws and theories in other branches of science that deal with complex systems and that stand in similar relations to physics as does chemistry. Materials science, geophysics, and meteorology are examples of such fields. (Christie & Christie 2000, p. 36).

The debates around the nature of laws in chemistry are ongoing and it is beyond the scope of this paper to contribute to this debate. However, it is important to problematise the complexity in the ways that philosophers of chemistry dispute the nature of chemical knowledge at large and the nature of laws in particular.

In summary, the suggestion offered by Christie (1994) is considered useful:

> Ultimately the best policy is to define 'laws of nature' in such a way as to include most or all of the very diverse dicta that scientists have chosen to regard as laws of their various branches of science. If this is done, we will find that there is not a particular character that one can associate with a law of nature. (Christie 1994, p. 629)

3.2.1 The Case of Periodic Law in Chemistry Textbooks

This section describes a case study of how a typical textbook covers the Periodic Table and how the discussion on the nature of the Periodic Law from a philosophical perspective could inform textbook revision. The purpose of this example is to illustrate how the philosophical dimensions of chemistry can be better captured in textbooks so as to ensure understanding of the epistemological aspects of chemistry. The coverage of the Periodic Table in chemistry textbooks has been highlighted to be problematic from a range of perspectives. For instance, Brito and colleagues (2005) argue that the important distinction of accommodation versus prediction in the context of Periodic Table is not covered in chemistry textbooks. In *A Natural Approach to Chemistry*, a textbook that is in current use in secondary schools in the USA, Hsu and associates (2010) dedicate a whole 31-page chapter to "Elements and the Periodic Table". The chapter begins with a section on the origin of elements in the universe. There are numerous occasions where the discussion on elements is linked to everyday contexts including the nature of metals on the hull of a boat, the human body and nutrition. A significant portion of the chapter is dedicated to the discussion on electronegativity, ionisation energy, the groups and series in the periodic table and an explanation of why compounds form using the Lewis dot notation. The chapter concludes with a set of open ended and multiple-choice questions.

The coverage of the Periodic Table does mention the notion of patterns but not laws. In the section describing the development of the Periodic Table and the contributions of Dimitri Mendeleev, the authors state that he *"was trying to figure out if there was any kind of organisation to the elements, some kind of pattern he could use to help organize them in a logical way.*" (p. 171). This reference is in contrast to the earlier discussion about the approximate nature of the Periodic Law. Indeed, predictions which are made from the so called Periodic Law do not follow deductively from a theory in the same way in which idealised predictions flow almost inevitably from physical laws. In this respect, the reference to a "logical way" in the textbook can be misleading in communicating the approximate nature of periodicity. The characterisation of the word 'periodic' is equally devoid of any specification of the approximate nature of the pattern: *"The Periodic Table is named for this because the rows are organised by repeated patterns found in both the atomic structure and the properties of the elements"* (p. 171). The explanation of the Periodic Table in terms of the atomic theory further stresses the logical ordering that the authors are emphasising throughout the text. In the discussion on the Modern Periodic Table, the authors state the following:

> At the time of Mendeleev, nothing was known about the internal structure of atoms. Protons were not yet discovered so the more logical ordering by atomic number was not possible. Today's table includes many more elements, and is ordered not by atomic mass, but by atomic number. However two things are still true of the periodic table, each column represents a group of elements with similar chemical properties, and each row (or period) marks the beginning of some repeated pattern of physical and chemical properties. While elements can be broadly categorized into metals, non-metals, and metalloids, an understanding that each column has similar chemical properties had lead to names for some of these element groups. (Hsu et al. 2010, p. 175)

What follows is the quantum mechanical models and the use of orbitals in explaining the organisation of the groups of elements. Considerable discussion is dedicated to establishing the role of valency in explaining periodicity including the introduction of the Lewis dot diagrams. The coverage of this textbook in terms of the viewing the Periodic Table as a taxonomical tool and a scheme without any explicit emphasis on the character of periodicity as a law-like feature of chemistry is consistent with observations of Christie and Christie (2003) mentioned earlier.

In his critique of Atkins' chemistry textbook coverage of quantum mechanical explanations, Scerri (1999) highlights a tendency among chemistry textbook writers to ignore the irregularities in the patterns in the Periodic Table:

> One is tempted to protest that in fact the proffered explanation does indeed require a new principle, namely the strange notion whereby the d- and f-subshells do not need to be complete for the shell itself to be classified as complete./.../ Surely it would not have detracted from the triumph of science to admit at this point, or anywhere in the book, that the assignment of electrons to particular orbitals is an approximation. In fact, Atkins could have made his story of the Periodic Kingdom all the more interesting if he had stated that even though his discussion was based around an approximate concept, we are still able to use it to remarkable effect to explain so many macroscopic and microscopic features connected with trends in the periodic table. (Scerri 1999, p. 302).

When the textbooks do cover the peculiarities, they are left un-discussed, as exemplified in the textbook mentioned earlier. Consider, for instance, the following excerpt:

> The transition metals illustrate a peculiar fact: the 3d orbitals have higher energy than the 4s orbitals!/../ Energy is the real, physical quantity that determines how the electrons act in atoms. The real energy levels correspond to the rows of the periodic table. The quantum number is an important mathematical construction, but is not the same as the energy level. (Hsu et al. 2010, p. 179).

Here there is a missed opportunity to raise some philosophical insights into the role of empirical evidence in model building in contrast to the mathematical and theoretical grounds for quantum mechanical models in chemistry. Scerri highlights this issue by inviting textbook writers to consider the grounds on which orbital models are related to periodicity:

> In addition, the failure to provide an adequate explanation of the 4s/3d question or a deductive explanation of the precise places where the elements appear to 'recur'

> should give us and Atkins grounds for suspecting that this model is not even all that empirically adequate. (Scerri 1999, p. 303)

So what would a revised chemistry textbook look like in light of this discussion so far? There are at least two issues that this coverage of the nature of the Periodic Law raises for consideration in textbook writing. First, the textbooks should elicit the approximate nature of the Periodic Law and specify the reference to the patterns in periodicity as an instance of law while highlighting the difference of interpretations of law in different branches of science. Second, the juxtaposition of the empirical versus theoretical dimensions of the orbital models should be teased out to clarify the different epistemological status of the Periodic Table in light of its historical and empirical foundation versus the incorporation of theoretical and mathematical characterisations since the advance of quantum mechanical models. Erduran (2007) has proposed elsewhere that an argumentation framework could offer a useful pedagogical strategy for eliciting different characterisations of laws (Erduran 2007) and suggested a potential activity could be structured as follows:

Claim 1: The periodic law and the law of gravitation are similar in nature. The term ‘‘law’’ can be used with the same meaning for both of them.

Claim 2: The periodic law and the law of gravitation are different in nature. The term ‘‘law’’ cannot be used with the same meaning for both of them.

These claims could be presented with evidence that would support either claim, both or neither. For example, the statement ‘‘a law is a generalisation’’ could support both claims while ‘‘the periodic law cannot be expressed as an algebraic formula while the law of gravitation can be’’ could support the second claim. The task for the students would be to argue for either claim and justify their reasoning. Further statements can be developed that would act as evidence for either, both or neither claim.

The inclusion of a framework that simulates the philosophical debate on the nature of laws in a comparative context between physics and chemistry will carry into the classroom the ways in which philosophers have conceptualised the nature of this particular aspect of scientific knowledge in these domains. Without a sense of a debate, textbooks reinforce the “received view” of science that projects a perception of a consensus when there is none. In summary, the inclusion of meta-perspectives offered by philosophical accounts of laws can provide insights into textbook accounts of laws whereby the particular nuances of chemical knowledge are better framed in terms of consistency with epistemological accounts on chemical knowledge.

4 The Nature of Explanation in Biology and Chemistry

4.1 Explanation in Biology

Explanation in biology differs from explanation in physics in that it does not aim to provide the typical “necessary and sufficient conditions”. Instead biological explanations aim to “gain partial, but ever increasing insights into the causal workings of various *life processes*.” (Brigandt 2011, p. 262). Mayr’s (1961) distinction between proximate explanation and ultimate explanation provides a basic dichotomy between at least two ways of explaining biological systems. In asking about how a phenomenon happens, the proximate explanation would address physiological or other processes that underlie the cause, while the ultimate explanation would address the phenomenon based on the organism's evolutionary history. The explanations do not contradict but rather complement each other by adding a different dimension: one causal and another historical.

Further expansion of explanatory breadth can be found in Tinbergen's (1952, cited in Sterelny & Griffiths 1999) four explanatory projects in biology, according to which it is possible to address questions about any behavior by proposing 4 different explanations: proximal, developmental, adaptive, and evolutionary.

> Tinbergen distinguished four questions we could have in mind in asking why a bittern stands still with its bill pointed directly at the sky. (1) We could be asking for a *proximal* explanation: an explanation of the hormonal and neural mechanisms involved in triggering and controlling this behavior. (2) We could be asking for a *developmental* explanation: an explanation of how this behavior pattern emerges in a young bittern. (3) We could be asking for an *adaptive* explanation: an account, that is, of the role this behavior currently plays in the bittern's life. (4) Finally, we could be asking for an explanation of how and why this behavior evolved in this bittern and in its ancestors. (Sterelny & Griffiths 1999, p. 50).

Press (2009) suggests that one of the ways in which philosophers contrast physics and biology is by appealing to differences between their respective explanations as they relate to the covering law model. He describes divergent views among philosophers of biology, as represented by Sober, Kitcher and Rosenberg regarding the applicability of the covering-law model in the context of biological explanations. After analyzing the different positions, Press (2009) concludes that there is a good fit between Hempel's covering law model and biological explanations, stating that "the differences between biological and physical explanations are merely a matter of degree. …. biologists, who deal with extremely complex systems, will need to rely relatively heavily on various sorts of approximation if they are to explain anything at all." (Press 2009, p. 374).

Branching off of these distinctions, philosophers of biology have detailed a number of explanatory types that support the aim of gaining insights about the 'causal workings' of biological systems without limiting their discussion to causal explanations. Wouters (1995), for example, outlines five different types of explanation: Physiological, Capacity, Developmental, Viability, and Historical/Evolutionary. These different types of explanation approach the same phenomena from different perspectives. To explain the circulatory system of a given organism for example, Wouters argues that physiological explanations focus on the types of events in the individual organism's life history, whereas a capacity explanation focuses on underlying causal explanations having to do with the structure of the heart and valves. A developmental explanation would focus on the development of the system (heart and vessels), while a viability explanation would focus on why structural differences between systems occur in different organisms. Finally, an evolutionary explanation would focus on differences in systems between organisms in the same lineage.

More recently, Wouters (2007) has proposed a sixth type, design explanation, in which a system in a real organism might be compared to a hypothetical one. Calcott (2009) makes the case for an additional type of explanation that he names, lineage explanation. This type of explanation aims to make plausible a series of incremental changes that lead to evolutionary change, focusing on a sequence of mechanisms that lead to the successive changes. Lineage explanations "show how small changes between ancestral and derived mechanisms could have produced different behavior, physiology and morphology". (Calcott 2009, p. 74). Consequently, they provide an additional "explanatory pattern" to account for evolutionary change.

Rose (2004) offers a fable that supports the discussion of how biological systems can sustain a variety of explanations. In this fable, five biologists are having a picnic when they noticed a frog jump into a nearby pond. Posing the question of what caused it to do so, led to five different answers. The physiologist reasoned that impulses traveled from its retina to the brain and then to the leg muscles. The biochemist pointed out the properties of the proteins, actin and myosin, whose fibrous nature enable them to move in a predictable way. The developmental biologist attributed it to the ontogenetic processes that occurred during early stages of cell division. The animal behaviorist attributed the cause to the snake that was lurking by, whereas the evolutionist discussed the role of natural selection in favoring those frogs that escaped their prey due their ability to detect them quickly and move fast in response, allowing them to survive and reproduce.

Of course, the question of legitimacy of teleological explanation in biology is important because of historical and pedagogical reasons. This is because attributing purpose to non-purposeful things or events, or attributing human qualities to non-humans can lead to questioning the credibility of the proposed explanation. The human tendency to assign purpose to everything seems to be nourished by the "sheer efficiency of biological structures [which] reinforces the illusion of purpose" (Hanke 2004, p. 145). Use by some biologists in a metaphorical sense makes these explanations likely to be misunderstood by non-experts, especially in educational settings. Some philosophers of biology differ in their degree of opposition to the use of these explanations but not necessarily to their problematic content—perhaps because they are well aware of their semantic affordances and limitations. Few philosophers strongly object to their use as expressed in Hanke's (2004) viewpoint that teleology is "bad not so much because it's lazy and wrong (which it is) but because it is a straightjacket for the mind, restricting truly creative scientific thinking" (p. 155).

The philosophical debates around these ideas have implications for educational settings but empirical findings can assist in making informed judgments regarding their use in educational contexts. Some science educators have cautioned against the use of anthropomorphic and teleological explanations in biology teaching out of concern for engendering misconceptions that can interfere with learning (Jungwirth 1979). However, a recent study called for the "removal of the taboo" regarding teleological and anthropomorphic explanations, arguing that results of an empirical cognitive study has shown that high school students' use of anthropomorphic or teleological explanations is not indicative of teleological reasoning, but seem to serve a heuristic value for learning as gleaned from the students' perspective (Zohar & Ginossar 1998).

The range of explanations described by Wouters (1995, 2007), Calcott (2009), and Rose (2004) illustrates the significance of invoking a diverse set of explanations for providing more comprehensive understanding of biological systems. Perhaps one of the overarching attributes of biological explanations is the notion of consilience in which different explanations need not be subsumed under one another and need not contradict with one another. The notion of consilience attributed to Wilson by Rose (2004), can perhaps be viewed as a pragmatic adaptation of the notion of 'consilience of inductions' developed by Whewell in his *Novum Organun Renovatum* (Morrison 2000). The diversity of explanatory types in biology is perhaps reflective of the "epistemological pluralism" (Rose 2004, p. 129) that is characteristic of the study of biological systems. This diversity is often obscured in biology education, not because it is difficult to communicate, but mostly due to the way the school biology curriculum is chopped up and structured in ways that limit reference at a given point in time to one or two explanatory emphases. This in turn limits teachers' and students' ability to experience the value of epistemological pluralism as a powerful vehicle for explaining and understanding phenomena in the life sciences.

4.1.1 Explanation in Biology Textbooks

Topics typically covered in high school biology textbooks in the United States include evolution, genetics, cell biology, and ecology. The approach to explicating these topics and the order in which they are presented varies significantly from one publisher to another[6]. For example in the SEPUP (2011) book, the ecology unit, typically presented in other books as the last unit, is second to a first unit on sustainability, a topic rarely addressed so explicitly in biology textbooks. However, explanations in the three textbooks consulted (see footnote) are similar to one another in that they are not differentiated from the rest of the text, but are blended in the narrative, becoming rather 'invisible'. The explanations follow the topical narrative, but there is no discernible attempt to provide a broader synthesis, weave cross-topical themes, or illustrate the notion of explanatory consilience.

4.2 Explanation in Chemistry

In the *Stanford Encyclopedia of Philosophy*, Weisberg and colleagues (2011) review the recent developments in the formulation of chemical explanations. These authors state that from the 19th century onwards, chemistry was commonly taught and studied with physical models of molecular structure. Beginning in the 20th century, mathematical models based on classical and quantum mechanics were applied to chemical systems. The use of molecular models has helped chemists to understand the significance of molecular shape (Brock 2000) and aided visual representation of structure and function of matter. One of the key scientific achievements of the twentieth century, the discovery of the double helical structure of DNA, was possible because of the use of physical models as explanatory tools (Watson 1968). The focus of chemical explanations entered a new phase with the advent of quantum mechanical theories and their applications in chemistry. The notion of 'explanation' in chemistry has centered in key debates involving not only models but also philosophical themes such as supervenience and reduction (Earley 2003) which will be referenced briefly later in the paper.

According to Weisberg and colleagues (2011), while exact solutions to the quantum mechanical descriptions of chemical phenomena have not been achieved, advances in theoretical physics, applied mathematics, and computation have made it possible to calculate the chemical

[6] The three textbooks reviewed in this section are BSCS 2003, Campbell, Reese, Taylor, Simon & Dickey 2009, and SEPUP 2011.

properties of many molecules very accurately and with few idealisations. This perspective is in contrast to those chemists who argue for employing simple, more highly idealised models in chemistry, which stems from the explanatory traditions of chemistry. In developing this point, Hoffmann illustrates two modes of explanation that can be directed at chemical systems: horizontal and vertical (Hoffmann 1998). Vertical explanations are what philosophers of science call "deductive-nomological explanations." These explain a chemical phenomenon by deriving its occurrence from quantum mechanics. Calculations in quantum chemistry are often used to make predictions, but insofar as they are taken to explain chemical phenomena, they follow this pattern. By showing that a molecular structure is stable, the quantum chemist is reasoning that this structure was to be expected given the underlying physics.

In contrast to the vertical mode, the horizontal mode of explanation attempts to explain chemical phenomena with chemical concepts. For example, Weisberg and colleagues (2011) use the example of SN_2 reactions as an example of horizontal explanations. The first year organic chemistry curricula include the relative reaction rates of different substrates undergoing SN_2 reactions. They state that an organic chemist might ask "Why does methyl bromide undergo the SN_2 reaction faster than methyl chloride?" One answer is that "the leaving group Br^- is a weaker base than Cl^-, and all things being equal, weaker bases are better leaving groups." This explains a chemical reaction by appealing to a chemical property, in this case, the weakness of bases. Vertical explanations demonstrate that chemical phenomena can be derived from quantum mechanics. They show that, given the (approximate) truth of quantum mechanics, the phenomenon observed had to have happened. Horizontal explanations are especially good for comparing and contrasting explanations, which allows the explanation of trends. In the above example, by appealing to the weakness of Br^- as a base, the chemist invokes a chemical property. This allows the chemist to explain methyl bromide's reactivity as compared to methyl chloride, and also methyl fluoride, methyl iodide and so on. Insofar as chemists want to explain trends, they make contrastive explanations using chemical concepts.

Apart from Hoffmann, earlier chemists argued that the nature of chemical explanations need not be overshadowed by quantum mechanical and reductive approaches. Consider, for instance, the perspective taken by Coulson:

> The role of quantum chemistry is to understand these concepts and show what are the essential features in chemical behavior. [Chemists] are anxious to be told … why the H–F bond is so strong, when the F–F bond is so weak. They are content to let spectroscopists or physical chemists make the measurements; they expect from the quantum mechanician that he will explain why the difference exists. … So the explanation must not be that the computer shows that [the bonds are of different length], since this is not an explanation at all, but merely a confirmation of experiment. (Coulson 1960)

Although both Coulson (1960) and Hoffmann (1998) defend the use of simple, idealised models to generate horizontal explanations, it is not clear that quantum calculations can never generate contrastive explanations (Weisberg et al. 2011). Although single vertical explanations are not contrastive, a theorist can conduct multiple calculations and in so doing, generate the information needed to make contrastive explanations. However the status of quantum mechanical explanations in chemistry is likely to be challenged for some time yet to come given the history of chemists' take on this issue. For example, Brown (2003) has drawn from cognitive sciences to illustrate that chemical explanations are metaphorical in nature and have a character that is distinguishable from representations employed in other fields of science: "…data are not explanatory in themselves. For the chemist to make effective use of powerful computational resources there must still be an underlying metaphorical model of what is happening in the conventional (chemical) sense." (p. 216). Even though chemical explanations involve the use of models and modeling (Erduran 2001), the meaning of the term 'model' or its function is not so straightforward particularly in relation to its import in chemical education. The presence of models in different disciplines related to chemical education, such as cognitive psychology and philosophy of science makes it even more difficult to come up with a single definition for the term "model" (Erduran & Duschl 2004).

A particular approach to chemical explanations include the reference to "structural explanations" (Harré 2003). Goodwin (2008) explains that in organic chemistry, the phenomena are explained by using diagrams instead of mathematical equations and laws. In that respect, the field of organic chemistry poses a difference in terms of the content of explanations from those in other physical sciences. Goodwin investigates both the nature of diagrams employed in organic chemistry and how these diagrams are used in the explanations. The diagrams particularly mentioned are structural formulas and potential energy diagrams. Structural formulas are two-dimensional arrangements of a fixed alphabet of signs. This alphabet includes letters, dots, and lines of various sorts. Letters are used as atomic symbols; dots are used as individual electrons, and lines are used as signs for chemical bonds.

Structural formulas in organic chemistry are mainly used as descriptive names for the chemical kinds. Thus a structural formula has a descriptive content consisting of a specification of composition, connectivity, and some aspects of three-dimensional arrangement. Structural formulas are also used as models in organic chemistry. For example, a ball and stick model is used in explanations. After characterising some features of structural formulas, Goodwin presents a framework of explanations in organic chemistry and describes how both structural formulas and potential energy diagrams contribute to these explanations. Then he gives the examples of 'strain' and 'hyperconjugation' to support his idea about the role of diagrams in capturing the nuances of explanations through structures in organic chemistry.

Debates on reduction – i.e. "reduction of axioms or laws of one science to the axioms and laws of a deeper putative science" (Scerri 2000b, p. 407) – has taken chemical explanations to its core in understanding what makes an explanation 'chemical'. Similar debates on reductionism have centred on issues related to philosophy of mind, particularly in the context of Multiple Realisability (e.g. Fodor 1974). Educational applications of such debates have been promoted though not yet realised at the level of schooling (e.g. Erduran 2005). One aspect of this debate has concerned the notion of supervenience. Two macroscopic systems that have been constructed from identical microscopic components are assumed to show identical macroscopic properties, whereas the observation of identical macroscopic properties in any two systems need not necessarily imply identity at the microscopic level. Chemical explanations have often been regarded as including microscopic, macroscopic and symbolic dimensions (e.g. Jacob 2001). The main position promoted in this debate is that the asymmetry in the way that properties and kinds of chemical entities are conceptualised suggest that chemical explanations cannot necessarily be reduced to explanations of physics – a realm of epistemology - even if ontologically chemistry might be reliant on physical principles.

4.2.1 Explanation in Chemistry Textbooks

Kaya and Erduran (2011) believe that structural explanations as discussed by Goodwin (2008) have relevance for chemistry textbooks. In their study of secondary chemistry textbooks across grade levels, they noted, for example, that for the 9th grade textbooks, topics such as ‘‘development of chemistry’’, ’compounds’, ’chemical changes’, ’mixtures’, and ’chemistry in our life’ all included structural explanations. Similar ways of coverage are noted in the textbook by Hsu and colleagues (2010). In the chapter on organic chemistry, for example, there are sections that illustrate and define “structural isomers”. Appendix A depicts the textbook reference to structural isomers of 2-pentane and isopentane. The description is “When a molecule has the same number and type of atoms, but a different bonding pattern, it is a structural isomer” (p. 541). The rest of the text is similar in terms of providing definitions for the characterisation of isomers. There are two types of representations that are both 2-dimensional but one represents the C and H atoms balls whilst the other does not. In this sense, there is potential for confusion for what counts as ‘structure’ when different levels of representations are superimposed.

4.3 Summary

This paper focused on the context, the definitions, and the types of laws and explanations in biology and chemistry and described some emphases and patterns that illustrate a number of similarities and differences between biological and chemical laws and explanations. For example, when the types of explanation in chemistry and biology are contrasted, the result is a diversity of types that are distinctive to the science in question. While biological explanations include viability and developmental explanations that draw closely from the nature of biological content, chemical explanations focus on the structural and representational explanations that are either based on quantum mechanical or simple chemical models. The context of debates around the nature of biological and chemical laws and explanations are also rather particular. Whereas reference to principles are common in biologists’ discussions of laws, the chemists are preoccupied with questions regarding axiomatisation and approximation.

5 Implications for Biology and Chemistry Education

This section provides some suggestions for how biology and chemistry education can be informed by investigations into the nature of laws and explanations. It illustrates the implications of the preceding discussion for teaching, curriculum and learning in biology and chemistry education. Design of instructional activities can exemplify more explicitly the role that variation and chance play in biological systems and enable students to explore the contribution of this uniqueness to shaping the formulation of biology’s ‘laws’ or principles. Awareness of the function of generalisations and principles in biology allows students to appreciate their role in the construction of biological knowledge, and enables them to realise that the scarcity of ‘laws’ does not diminish the 'power' of the generalisations/principles they study or reduce the status of biology to a "soft science".

In terms of chemistry teaching, the goals of teaching could include the broader aims of promoting students' understanding of how some chemical laws like the Periodic Law are generated and how they differ from laws in chemistry or other sciences. Lesson activities could acknowledge the observation that, for instance, the Periodic Law will be manifest in the classroom via comparative discussions about the trends in the chemical and physical properties of elements. Furthermore, engaging students in the process of the derivation of some of these trends is likely to give them a sense of how laws are generated and refined in chemistry. How can such discussions of laws, then, be manifested in the classroom? Earlier work has identified strategies such as questioning and discussion in chemistry teaching (Erduran 2007) that can be extended to biology teaching due to their broad pedagogical scope. For example, students could be presented with alternative accounts of scientific laws – those derived deductively and those that are derived with approximation and induction in mind – and asked to question, compare, evaluate and discuss them in relation to other products of scientific knowledge.

This review also has implications for the design of curricula for the inclusion of biological and chemical content knowledge. With respect to biology, curriculum materials should attempt to communicate more explicitly elements of "epistemological pluralism" and how biologists search for consilience among a proposed family of explanations. Including these ideas in the curriculum should not be limited to presenting isolated narratives about how biologists work but should be reflected in developing more integrated and coherent content frameworks. This is necessary for promoting a more holistic and contextual understanding of structures and processes in biotic systems. Even though the chemistry curriculum typically covers structural explanations as described by Goodwin (2008) across various levels of schooling, the meta-perspectives on the nuances of these explanations are not typically part of either curriculum materials or textbooks (Kaya & Erduran 2011).

The discussion about the power and limits of biological and chemical laws can be initiated in curriculum resources by focusing more explicitly on what Mendel's Laws or the Periodic Law do and fail to do. Curricula and textbooks tend to cover laws in quite an ambiguous and limited manner (i.e. McComas 2003) and often present laws in different science fields on equal footing. That is, when certain generalisations are labeled as laws, textbook authors do not contextualise or explore what that label means. From the point of view of a teacher or student, a law in physics (e.g. Newton's) carries the same epistemic and ontological significance as a law in biology (e.g. Mendel's) or chemistry (e.g. Periodic). In some cases, neither Mendel's law nor the Periodic law are introduced as laws and consequently an opportunity to discuss the implications of these terms is lost. A study of Turkish chemistry curricula and textbooks, for example, revealed that there is little or no differentiation of the meta-perspectives on the nature of knowledge (Kaya & Erduran 2011). Other studies on textbooks (e.g. Niaz & Rodriguez 2005) point to lack of attention to NOS features in general, let alone the nuanced distinctions addressed here. Understanding the relationship of laws and explanations to theories in biology and chemistry demands a deliberate undertaking from historical and contemporary perspectives.

Furthermore, chemistry curricula often contain conceptual mistakes and thus demand closer examination. For example, the notion ‘‘one molecule - one shape’’ is widespread, and results in students’ construction of a misconception where molecules are static, not oscillating and taking on different shapes (Kaya & Erduran 2011). The dynamic nature of molecular shape is an inherent aspect of chemical explanations. Coverage of structural explanations with meta-level perspectives is likely to minimise misconceptions about the dynamic nature of molecules. Chemistry curricula also need to scaffold students’ understanding of how chemical explanations can rest on structural models and how these differ from, for instance, historical or evolutionary explanations in biology. Design of instructional activities would, then, need to acknowledge the observation that explanations will be manifest in the classroom via discussions of the signs and symbols that make up the alphabet of structures represented in chemistry. Engaging students in the generation, evaluation and application of structural explanations in chemistry is likely to improve their understanding of how chemical language and explanation relate to each other.

There are important reasons for why biology and chemistry learning should be informed by the issues raised in the paper. Familiarising students with different *types* of explanation in biology may mitigate against straying into teleological sidetracks, favoring the capacity/causal type, or privileging some types of explanation over others (those dealing with the how over those dealing with the why). The tendency of students to favor experimental over historical explanations, for example, has been documented in the context of evolutionary theory (see for example, Dagher & BouJaoude 2005). Thus, biology learning could focus on constructing and utilising a broad range of biological explanations for a given phenomenon and applying this kind of reasoning to multiple contexts/phenomena. In support of this kind of learning, there needs to be a re-structuring of the content/curriculum, so that explanations addressing different aspects of the phenomenon under study are not isolated from each other as is typically the case (e.g. evolutionary and ecological concepts are rarely discussed in relation to each other or to physiological concepts in school science). With respect to chemistry learning, the articulation of structural explanations with meta-level perspectives is likely to assist in understanding the dynamic nature of molecules. As discussed earlier, a common problem in chemical education concerns the interpretation of molecular models and straying onto static notions of molecular structures as sidetrack in learning outcomes. Given the centrality of molecular structure and modeling in chemistry, improvement in the learning of the structural explanations is likely to have positive impact on understanding other related areas of chemistry.

In summary, the aspects of laws and explanations in biology and chemistry emphasised in this paper are not exhaustive but are representative of the types of issues that concern us as science educators interested in improving students’ understanding of science. This understanding will be enriched if students are provided multiple opportunities to develop meta-level understanding of how particular domains of science engage with some of the key aspects of scientific knowledge such as laws and explanations. There has been long standing criticism of science education in failing to enable students to understand the nature of science, scientific knowledge and scientific knowledge development. Whilst science educators have acknowledged that perspectives from history and philosophy of science can promote a deeper understanding of the nature of science, the role of the nature of disciplinary knowledge has been under-investigated within the science education research community. The aim of this chapter was to articulate the nature of laws and explanations in biology and chemistry so as to extend and enrich the previous agendas for teaching the nature of science using domain-specific epistemologies to describe key debates and features related to disciplinary knowledge. Further research in this area is needed to further clarify, refine, challenge, and expand some of the claims presented in this paper.

Acknowledgements The authors wish to thank the five anonymous referees who provided valuable feedback on earlier versions of this chapter.

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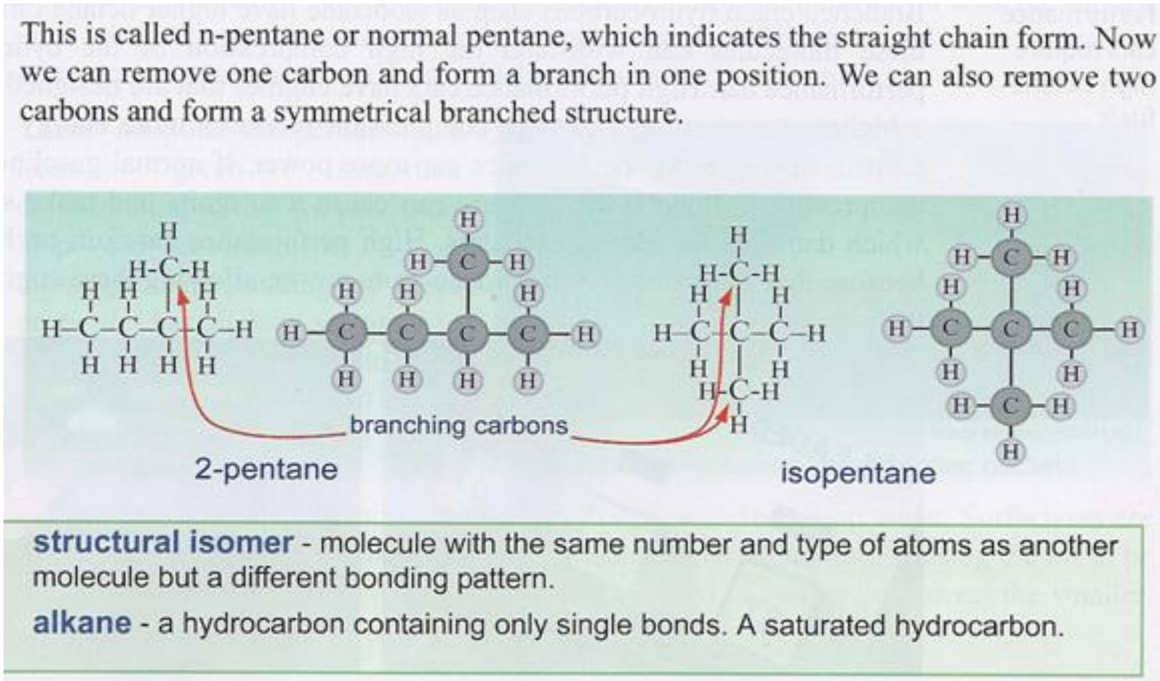
Appendix A Source of potential confusion about structural explanations in a high school chemistry textbook (Reproduced from Hsu et al. 2010, p. 541).


This is called n-pentane or normal pentane, which indicates the straight chain form. Now we can remove one carbon and form a branch in one position. We can also remove two carbons and form a symmetrical branched structure.

structural isomer - molecule with the same number and type of atoms as another molecule but a different bonding pattern.

alkane - a hydrocarbon containing only single bonds. A saturated hydrocarbon.

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In this version, we cleaned up typos/language and replaced an Irzik & Nola 2011 reference with a reference to their handbook chapter.