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Revisiting Analogical Reasoning in Science Teaching: From the Reception to the Production Paradigm

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Abstract

Extensive research on science education has evidenced the effectiveness of analogies as a didactic device that can facilitate the learning process of abstract concepts when the analogies are appropriately and effectively used. This paper summarises research on such a use of analogies but also switches attention to student self-generated analogies, as opposed to analogies generated by education researchers, teachers, or authors of science textbooks that the literature has largely focused on. It discusses the heuristic use and efficacy of student self-generated analogies as a tool in approaching and correctly understanding what is new and unknown which has value in science teaching and learning. Such use of analogies derives from a summary of our research with a wide age range of students, who, when asked to make predictions in situations never considered before and to then provide explanations about these predictions, self-generated analogies. As it was found in students' explanations, it was by reasoning on the basis of these self-generated analogies that they approached the situations they were presented with and most, but not all, made a scientifically incompatible prediction for. There has been heuristic use of student self-generated analogies identified that can be used in revealing a scientifically compatible way of reasoning on the basis of student self-generated analogies which can be also productively used in the process of science teaching.

Keywords: *Self-generated Analogies, Analogies in Science Teaching, Heuristic Analogies, Analogical Reasoning*

1. Introduction

Within the realm of science education, analogies have long been recognised as instructional tools that have the potential to facilitate learning by the bridging between abstract scientific concepts and students' existing knowledge [1][2]. Indeed, when effectively used, analogies can help in understanding the unfamiliar and unknown based on what is familiar and known. However, much of the research in science education on analogies has predominantly focused on what has been termed as the *reception paradigm* [3] wherein teachers and/or textbook authors provide pre-determined analogies they generate for students to make use of. Such an approach may constrain students in constructing their own understanding on the basis of what is known to them than to those that generate the analogies thus limiting both their active engagement in analogical reasoning and development of scientific knowledge and inquiry skills. This paper draws on a synthesis of the previous research on student-self generated analogies by examining their heuristic potential. The purpose is to discuss how the act of self-generating analogies can allow students to actively construct knowledge, make predictions about unfamiliar situations, and reveal their underlying reasoning which has value in the teaching process and illustrate how, in some cases, albeit atypical, such a reasoning can be compatible and lead to a scientific understanding.

1.1 Background

Historically, the use of analogies can be traced back to the very early times of inquiry. Philosophers like Aristotle, for example, discussed argument construction by analogical reasoning in the sense of passing from known similarity properties to extending these to further possible similarities [4]. In Topics [5, p. 108a], Aristotle explains that "likeness should be studied first in the case things belonging to different genera, the formula being A: B = C: D… and as A is in B, so is C in D". In a similar vein, and despite the significant differences in their epistemological positions – i.e., Plato emphasising the theory of forms where knowledge is regarded as in an absolute and unchanging perfect form, and Aristotle focusing on the role of observation and experience in acquiring knowledge, Plato also recognised the inherent paradox of inquiry and how what is known is essential in the process of inquiring. In Socrates' words in Plato's paradox of Meno [6]:

> You argue that a man cannot enquire about that which he does not know; for if he knows, he has no need to enquire; and if not, he cannot; for he does not know the very subject about which he is to enquiry (p.68).

This paradox, which questions the how and the necessity to seek what is already known, lies at the core of analogical reasoning and the problems they are used to solve. In other words, to approach the unfamiliar and unknown, one must relate it the familiar and the known. Plato is renowned for the utilisation of analogies as devices employed to illustrate abstract and complex philosophical concepts like the allegory of the cave to convey the concepts of knowledge and inquiry and, among many others, the idea of initial ignorance and the difficulty of moving from opinion to true knowledge [7].
Later scientists also employed analogies to simplify and convey abstract ideas on the one hand and conceptualise complex phenomena and develop theories, on the other. For example, Isaac Newton in his *Principia* draws on analogical relationships between the gravitational force involved in making an apple fall and the same force making the moon move [8]. In addition, casual analogies and illustrations drawn from experiences appear frequently in Galileo Galilei's dialogues when comparing the motion of planets to that of rolling balls thereby enabling an understanding of inertia to be achieved [9]. This historical precedent underscores the efficacy of analogical reasoning as a means of making sense of the natural world and in supporting knowledge acquisition on the basis of prior knowledge.
A more direct line of evidence is the explicit reference on the use of analogies by scientists when problem-solving and the role they play in the development of a new theory. As the well-known astronomer Johannes Kepler wrote: "And I cherish more than anything else the analogies, my most trustworthy masters. They know all the secrets of Nature and they ought to be least neglected in Geometry" [10, p.12]. Also, the nuclear physicist Sheldon Glashow [11], who was awarded the 1979 Nobel Prize, made a reference to the use of analogies developing the unified weak and electromagnetic interactions theory:

> I was led to the group SUX2 x U (1) by analogy with the approximate isospin-hypercharge group which characterises strong interactions (…). Part of the motivation for introducing a fourth quark was based on our mistaken notions of hadron spectroscopy. But we also wished to enforce an analogy between the weak leptonic current and the weak hadronic current … (p. 1321-1322).

Other historical studies [12] and field studies [13] indicate that experts use analogies as a reasoning tool with more direct evidence of experts using analogies to resolve conceptual difficulties during problem-solving also provided in the literature [14]. The aforementioned kinds of remarks are strongly suggestive of the function of analogies as tools of thought that can facilitate the understanding of an unknown phenomenon or, more generally speaking, an unfamiliar situation.

2. Analogical Reasoning in Science Education

The use of analogies in education more generally has a rich historical context and has been widely recognised as a potent instructional tool as evidenced early in the teaching of classical philosophers such as Plato and Aristotle discussed above. Research in science education has also long established the role of analogies in science teaching in bridging the gap between familiar and unfamiliar concepts to facilitate the learning of abstract scientific ideas thus leading to conceptual change [1]. From a pedagogical point of view, this approach aligns with constructivism according to which knowledge is actively constructed through connections to prior experiences.
The educational implications of analogies were further developed in the latter half of the 20th century, with a focus on the cognitive mechanisms involved in analogical reasoning and frameworks for an understanding of analogy generation. This past work has further confirmed that analogies could enhance science learning and problem-solving abilities, by providing a framework for students to transfer knowledge from a known and familiar, to an unknown and unfamiliar domain [15]. This is particularly relevant in science teaching as concepts are often counter-intuitive, abstract, complex and not easily grasped by students.

2.1 Analogical Reasoning within the Reception Paradigm

Analogies in science teaching can be situated within the *reception* paradigm [3], as their didactic use implies that students receive an analogy generated by either the teacher or the author of the textbook and apply it in an intended way which is predetermined by the analogy generator. Although such a use has been effective [16][17], it assumes that students do have the necessary prior knowledge and are familiar with what the generator believes constitutes the known domain. It also assumes there is an understanding of what similarities are to be mapped and transferred from this domain to the unknown and unfamiliar one. This may be problematic making such a didactic use of analogies a *double-edged sword* where a teacher perceives as known what might be completely unfamiliar to students [18]. Even if students have some familiarity with the known domain, they might interpret it differently to that which the generator intended; thus, leading to unintended learning and give rise to misconceptions.
For example, the Bohr planetary model can be used as a visual analogy for students to develop an understanding of the electron orbits in an atom. However, as with every analogy, this may break down as students might erroneously assume that just like the planets in the Bohr's model, electrons follow fixed elliptical paths rather than existing in probabilistic clouds with quantum mechanics explaining their motion, not classical mechanics. Another example is the water flow analogy [19] which, when effectively used, can facilitate the understanding of electrical current through a mapping of the flow of electrons to the flow of water through a pipe. However, in order to extend this analogy further for an understanding of more complex concepts like voltage, for example, as analogous to water pressure they would need have an understanding of pressure in fluid systems. Therefore, the effectiveness and their use within the *reception* paradigm requires a prior assessment of familiarity and knowledge of the known domain, an understanding of what is to be mapped and signalling where analogies break down as well.

2.2 Analogical Reasoning within the Production Paradigm

As the field has evolved, there has been a shift towards analogies within the *production paradigm* [3] where instead of ready-made analogies, students self-generate analogies in an attempt to approach the unknown and unfamiliar. This perspective is a form of more authentic analogical reasoning which better aligns with a constructivist approach to learning. This is as students themselves are drawing on their prior knowledge to map and transfer analogical relations to leverage what is unknown to the unknown and unfamiliar situations thus being more actively engaged in the reasoning process.

2.3 Student Self-Generated Analogies as Diagnostic Tools

Our past work [20][21] has shown that in most cases students' analogical reasoning leads to an erroneous understanding and gives rise to popular misconceptions. This is mostly because their prior knowledge is experientially grounded and their everyday experiences their analogies are founded upon misalignment with the unknown and unfamiliar domain under consideration [21].
For example, we have asked students in a previous study [22] to reason about a novel situation (situations they have not considered before, or at least in the way these were presented to them) regarding the concept of gravity and free fall. Students were asked to predict which of two identical boxes, one with an elephant and the other with an ant, that are left to fall from the same height in the absence of air resistance hits the ground first. The below example of a 12-year-old student response illustrates explanations in which students involved an analogy in an attempt to justify their prediction reflecting a popular misconception that heavier means faster [23].

> *Because the elephant is heavier than the bug, thus when you cut simultaneously both of the ropes the elephant falls first and the bulb A will switch on first. I have seen in everyday life a whole book falling faster than one single page of a book.*

This self-generated analogy from an every-day observation that a book falls faster than a page which is accurate in everyday situations where air resistance is present, and indeed heavier objects fall faster. It is the limitation of such an experientially grounded knowledge of falling objects in the particular context where air resistance is considered that misaligns with the novel situation where it is not. In a vacuum, the mass of objects does not affect their acceleration due to gravity and thus, in this novel situation, both boxes fall at the same rate reaching the ground at the same time. This example indicates that misconceptions commonly originate from an intuitive, experience-based reasoning that has not been refined for students to realise its context limitation [21]. Such student-generated analogies have the potential to reveal not only the underlying knowledge that informs their reasoning and give rise to misconceptions but also their thought processes for teachers to then explicitly address the importance of context, clearly differentiating between the context of everyday observations and their range of applicability to other situations.

2.4 Self-generated Heuristic Analogies

In previous work, we have identified student self-generated analogies that functioned heuristically in approaching novel situations and developing an understanding compatible with the scientific account. The term *heuristic* etymologically derives from the Greek verb *heurískō* meaning to *discover* or to *find out* and thus is used to describe a self-generated analogy where students access a familiar situation and construct analogical relationships between this and an unfamiliar situation on their own, with no guidance. In this sense, these analogical relationships enable students to *find out* or *discover* similarities, draw inferences and transfer them from the known and familiar domain to the unknown and unfamiliar. While all student-generated analogies generally allow students to *find out* or to *discover* similarities to, most often incorrectly [21], understand the unfamiliar based on the familiar, we define the term *heuristic* differently to that in other studies [24]. We use this to distinguish between self-generated analogies that lead to incorrect understanding and those that help students *find out* or *discover* scientifically compatible relationships, leading to the development of a correct, scientifically compatible understanding [25]. In this way, *heuristic* is used for these *Eureka* (cognate word deriving from *heurískō* and is a transliteration of an exclamation attributed to Archimedes) moments, when student self-self-generate analogies and reasoning on their basis leads to an understanding that is compatible with the scientific account. Although no claim is made about students' reasoning being identical to that of science experts like Archimedes *Eureka* moment of arriving to the principle of buoyancy, aspects of expertise in analogical reasoning and use of the self-generated analogies in developing a scientific understanding should not be ignored.

For example, we asked students in a previous study [22] what happens to the level of water in a glass when an ice cube in it melts. Students' heuristic analogical reasoning led them to access experiential knowledge where sand or sugar is removed from a cat sandbox or jar respectively and think of the space left like the volume of water displaced by the ice cube in the glass of water. By further inferring that when the ice cube melts it changes to a volume of water that perfectly fills the space that was previously occupied by the displaced water due to the ice cube, they reached a correct prediction that the level of the water in the glass remains the same. Despite the atypicality of such cases [21] and that the understanding is scientifically incomplete, we have argued [25] that heuristic analogies provide a familiar starting point that can be extended to an accurate and complete scientific understanding. In this particular case of the melting ice cube in a glass of water, students' heuristic analogies can be primarily used to illustrate the concept of displaced volume that can in turn be related to density and the buoyant force introducing, in this way Archimedes' Principle.

3. Conclusions

Analogies in science teaching can go beyond their use as instructional devices within the reception paradigm where students are passively receiving ready-made analogies by their teachers or presented to them in textbooks. Such a use, even when effective, limits involvement in analogical reasoning and active learning. Instead, analogies within the production paradigm can provide a more authentic involvement in analogical reasoning. In this sense, students' involvement in self-generating analogies would allow teachers to identify what knowledge they draw upon, the analogical reasoning they employ and the inferences they make thus serving as a valuable teaching resource for the diagnosis of misconceptions and their origin. This would not only reveal their thought processes and erroneous understanding but also the contextual basis of their prior, often experientially grounded, knowledge. Heuristic analogies, on the other hand, can be leveraged through a dialogue where opportunities are provided to elaborate on self-generated analogies and make comparisons with the heuristic ones thus creating an interactive learning environment where students co-construct knowledge.

Self-generated analogies can thus enable teachers to target and address the roots of misconceptions and the limitations of the context from which they arise, while utilising the heuristic analogies as a scaffold towards scientific understanding to allow for more effective science teaching. This requires an environment where dialogue can flourish and students are given the opportunity to talk science, self-generate analogies and discuss these in the science classroom. In this way, teachers can cultivate a more dynamic and student-centred learning environment, where students co-construct knowledge and refine their own understanding rather than passively receiving information. Such an approach aligns more naturally with constructivism as new knowledge is constructed on the basis of what is known to the students, and social constructivism in that this new knowledge is facilitated through an interactive and collaborative setting.

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