Making Energy Easy: Interacting with the Forces Underlying Chemical Bonding Using the ELI-Chem Simulation

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Abstract

This work seeks to develop and explore high-school chemistry students' conceptual understanding regarding energy changes during chemical bonding. Lacking the force-based explanation, students rely on intuitive heuristics, thinking that energy is released during bond breaking, that energy is required to form a bond, or that energy is released in both bond formation and breaking. Our ELI-Chem learning environment enables interaction as an atom with another atom while experiencing the attraction and repulsion forces and observing the resultant potential energy diagram in real time. The theoretical framework is based on embodied learning theory by relating conceptual learning to bodily experience. The study uses mixed methods that include visual clustering, quantitative and qualitative data analysis. Research was conducted with six students using a pretest-intervention-posttest design. Learning with the ELI-Chem environment provided students the vocabulary, concepts and principles that are required to shift from either rote articulation or an octet-based explanation to a more force-based understanding. In the post-interview, they could explain the scientific bonding energetics and chemical stability using the relationships between attraction and repulsion electrical forces.

Keywords: chemical energy, attraction/repulsion forces, chemical bonding, embodied learning, simulation.

Introduction

This study addresses high-school chemistry students' difficulties in understanding the energetics associated with chemical bonding. Many students believe incorrectly that energy is released during bond breaking, that energy is required to form a bond, or that energy is released in both bond formation and breaking (Becker & Cooper, 2014; Cooper & Klymkowsky, 2013; Galley, 2004; Teichert & Stacy, 2002). One possible source for these ideas is the abstract nature of energy and lack of experience with chemical bonding -students often think of atoms as physical entities for which energy is needed to bring them together (Boo, 1998), or as coiled springs that release energy when relaxed (Hapkiewicz, 1991). Another possible source are current teaching approaches that do not relate energy to forces (Becker & Cooper, 2014; Nahum-Levy, Mamlok-Naaman, Hofstein, & Krajcik, 2007; Taber, 2002).

We designed and developed an Embodied Learning Interactive environment, ELI-Chem (Authors, 2015) to support these difficulties. ELI-Chem removes the abstraction by providing bodily experience with the molecular level as proposed by embodied learning theory (Barsalou, 1999). ELI-Chem is based on a mathematical simulation of attraction-repulsion forces between atoms thus emphasizing the force-based teaching approach.

The present study continues our previous research (Authors, 2017) in which chemical bonding was learned as a dynamic equilibrium between attractive and repulsive forces. Herein, we add another layer upon the force-based view which connects it to energy changes. We describe research conducted with students interacting as an atom with another atom, exploring forces and potential-energy diagrams. The working hypothesis is that bodily experience with the underlying electrical forces provides a strong foundation for understanding energy changes during chemical bonding and related concepts such as stability or bond-strength.

Theoretical Background

Energy is a core concept for all STEM disciplines, and is considered as both a "disciplinary core idea" and as a "crosscutting concept" (NGSS, 2013; NRC, 2012). The multiplicity of definitions across disciplines in addition to its abstract nature makes understanding energy most challenging. In chemistry, where the objects themselves –atoms and molecules– cannot be observed and behave counter-intuitively, grasping the energy changes during the interactions between them is more difficult. Moreover, current teaching approaches do not relate energy to the underlying electrostatic interactions between atoms (Becker & Cooper, 2014; Nahum-Levy et al., 2007; Taber, 2002), leading to inflexible heuristics and rote learning rather than providing tools for understanding how forces impact energy changes.

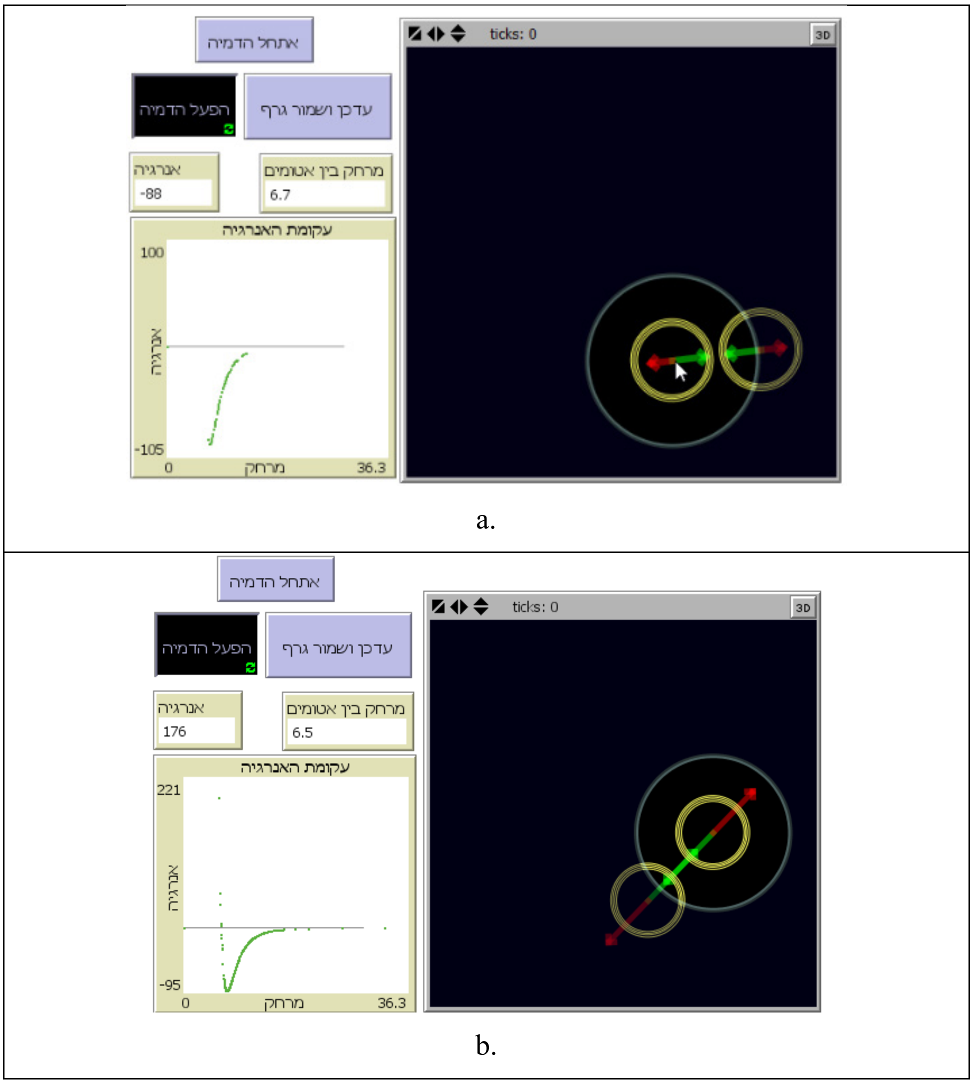
Indeed, numerous studies reported that chemistry students lack a proper foundation to understand the relationships between atomic–molecular structure, electrostatic forces and energy (Becker & Cooper, 2014; Cooper & Klymkowsky, 2013; Lindsey, 2014; Shahani & Jenkinson, 2016; Taber, 2009; Venkataraman, 2017). Instead, they reason based on the 'octet rule', i.e., atoms form chemical bonds to "complete a set of eight electrons in the last energy level"; this is their most stable state (Taber, 2002). Without the knowledge of the underlying electrostatic forces students are confused, they contradict themselves and have difficulties to reconcile the conflicts (Teichert & Stacy, 2002). The most common contradiction among students is that 'energy is required in both bond formation and bond breaking' (Barker & Millar, 2000; Boo, 1998; Cooper & Klymkowsky, 2013; Galley, 2004; Hapkiewicz, 1991; Lindsey, 2014; Teichert & Stacy, 2002). Becker and Cooper (2014) argue that since students lack any significant reasoning power, they rely on intuitive interpretations of energy and on heuristics. Thus, some students think that energy is required to form bonds based on their experience in the macroscopic world where energy is needed to build structures (Boo, 1998). They assume incorrectly that the closer the atoms, the greater the energy of the system (Lindsey, 2014; Nagel & Lindsey, 2015), suggesting that they are based on the intuitive rule of "More A—More B" (Tirosh & Stavy, 1999). Other intuitive interpretations related to chemical energy include the ideas that chemical reactions are driven by external interventions such as heating (Boo, 1998), that endothermic reactions cannot be spontaneous (Boo, 1998; Thomas & Shwenz, 1998), and that strong bonds "store" more energy, thus release a significant quantity of energy when broken (Becker & Cooper, 2014; Galley, 2004; Hapkiewicz, 1991; Teichert & Stacy, 2002).

Both national science education documents (NGSS, 2013; NRC, 2012) and educational researchers (Becker & Cooper, 2014; Galley, 2004; Nahum-Levy et al., 2007; Taber, 2009) propose presenting chemical bonding using the forced-based explanation based on Lennard-Jones potential to improve students' understanding. According to this approach, the attraction and repulsion forces between atoms arise from their subatomic structure and govern the behavior of atoms and molecules. Thus, a bond is formed due to electrical forces; it is most stable when the forces are balanced. At this point the net force is zero and the potential-energy of the system is minimal. Therefore, bond formation happens spontaneously -the energy decreases and released, and breaking bond requires energy in order to overcome the balance between the forces.

In order to overcome the difficulties posed by the abstract nature of the topic we turned to embodied learning theory. This theory relates cognition to physical body-world interactions, claiming that a full understanding involves a mental simulation of perceptual experience when retrieving the information about it (Barsalou, 1999; Wilson, 2002). Applied to education, learning environments are designed to generate a learner's embodied experience of the phenomenon being studied. Studies show that embodied learning environments enhance understanding either when the action is performed by the learner such as gestures (Abrahamson et al., 2012; Botzer & Yerushalmy, 2008), or when the action is performed on the learner such as a haptic-force exerted on the body (Reiner, 1999).

Our ELI-Chem provides bodily experience as an atom bonding with another atom and the associated forces and energy. ELI-Chem offers sensory-motor experiences at increasing degrees of embodiment from gesture control to force-feedback as part of a forced-based computer simulation. The present study focuses on the first degree of embodiment, and is part of a larger project that compares learning through these different devices.

The Learning Environment



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מרחק בין אטומים 6.7

a.

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b.

Figure 1. ELI-Chem screen shots. a) At bond length forces are equal. b) When too close repulsion forces dominate. Attractive (green) and repulsive (red) forces, and the potential-energy curve, are computed and displayed.

The ELI-Chem environment (Zohar & Levy, 2015, 2016) makes the molecular level perceptually accessible and physically manipulable, and is geared to enhance conceptual understanding of the underlying forces of bonding and of the involved energy changes. It is based on a computer simulation that was created with NetLogo (Wilensky, 1999). The Lennard-Jones potential (Jones, 1924) between two neutral atoms is modeled, displaying the resultant attraction-repulsion electrical forces and the related potential-energy as a function of the distance between the two atoms. Students select an atom, drag it across the screen closer and further away from another atom and experience the resulting attraction/repulsion forces while observing the resulted potential-energy diagram in real-time (Figure 1).

Methods

Approach. This study uses mixed methods that include visual clustering, quantitative and qualitative data analysis.

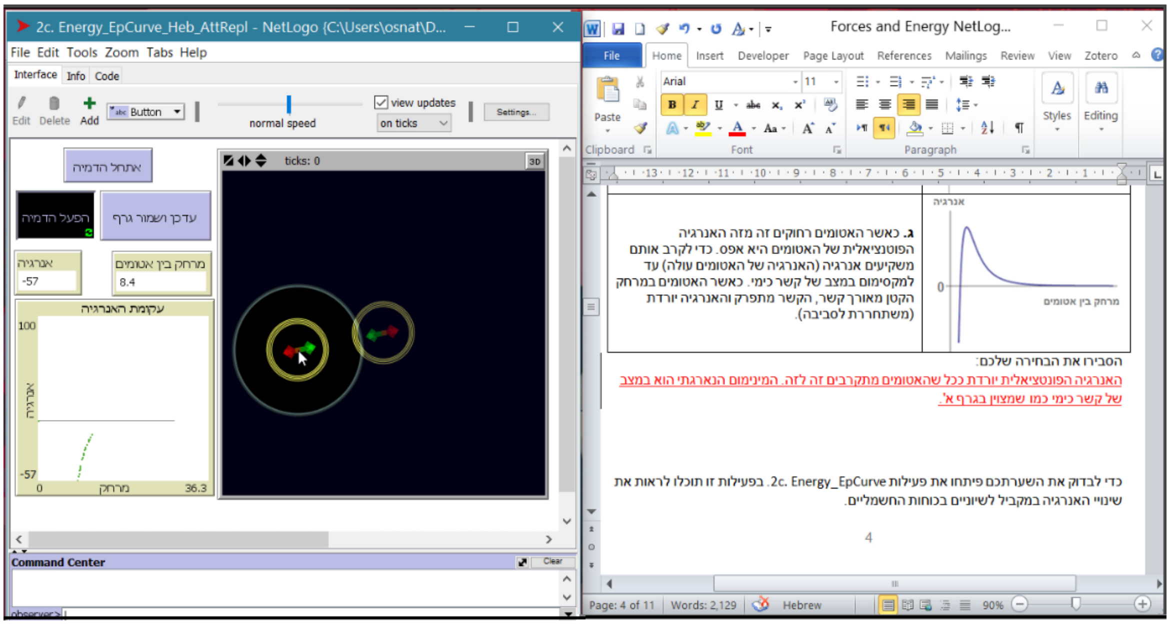
Participants. Six 12th grade students studying towards chemistry matriculation examinations at the highest-level, from a north peripheral region in Israel. Participants were sampled opportunistically as the activities were voluntary and outside of school hours.

Design. The study design is pretest-intervention-posttest.

Procedure. Sessions included a 10-minutes pre-interview, a 40-minutes guided hands-on activity with the simulation (Figure 2) and a 10-minutes post-interview. Main concepts addressed: energy in chemical bonding, repulsive and attractive forces, potential-energy curve, bond stability and bond-strength.

Data collection. The pre-post semi-structured interviews were similar and consisted of eight to ten conceptual questions about forces and energy in bonding and one attitudinal question in the post-interview. Students' interviews were video-captured. Their activities with the simulation were both screen-captured and video-captured.

Data analysis. Videotapes were transcribed. The transcripts of the activity were coded for the most common knowledge-elements, i.e., ideas or concepts upon which students base their explanation (Sherin, 2013).



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מרחק בין אטומים: 8.4

ג. כאשר האטומים רחוקים זה מזה האנרגיה הפוטנציאלית של האטומים היא אפס. כדי לקרב אותם משקיעים אנרגיה (האנרגיה של האטומים עולה) עד למקסימום במצב של קשר כימי. כאשר האטומים במרחק הקטן מאורך קשר, הקשר מתפרק והאנרגיה יורדת (משתחררת לסביבה).

הסבירו את הבחירה שלכם:

האנרגיה הפוטנציאלית יורדת ככל שהאטומים מתקרבים זה לזה. המינימום האנרגתי הוא במצב של קשר כימי כמו שמצוין בגרף א'.

כדי לבדוק את השערתכם פיתחו את פעילות 2c. Energy_EpCurve. בפעילות זו תוכלו לראות את שינויי האנרגיה במקביל לשינויים בכוחות החשמליים.

Figure 2. ELI-Chem pedagogical guide

Findings

In both pre- and post-interviews students were asked to define chemical energy, to describe the energy changes during chemical bonding, to explain bond stability and bond strength. Presentation of the results includes description of the emergent knowledge-elements and their frequencies.

Description of the Knowledge-elements

During the pre- and post-interviews nine common knowledge-elements emerged and categorized by their related theoretical underpinnings (Table 1).

Table 1. Knowledge-elements: Dimensions, Definitions and Examples

Dimension	Knowledge-element	Definition	Example
Energy	Bond formation – energy released (correct)	Chemical bonds release energy as they form.	"The energy is released while new bonds are being formed".
	Bond formation – energy required (incorrect)	Energy is required to form chemical bonds.	"You need to invest more energy to form it [a bond, in comparison to breaking it]. Because you need to push the elements [atoms] together. Like pushing them, bringing them closer to each other."
	Bond breaking – energy required (correct)	Energy is required to break chemical bonds.	"It is worthwhile energetically for atoms to be in a bond. That is, if we want to break a bond, to destabilize the bond, we need to invest energy so that… so that the atom will be destabilized and the atoms themselves can separate from each other."
	Bond breaking – energy released (incorrect)	Chemical bonds release energy as they break.	"We've learned in biology that there is some kind of molecule whose internal energy is very very high. So when it breaks down, it releases lots and lots of energy."
Forces	Attraction	There is an attraction between atoms.	"A chemical bond is when two atoms are attracted to each other."
	Repulsion	There is repulsion between atoms.	"They [the atoms] will approach until both nuclei will repel each other because both are positive".
	Equal forces	A stable state of a bond is when attraction forces balance repulsion forces.	"A stable state between two atoms or two molecules is when they attract each other with a force that equals the force that they repel each other."
Octet	Full energy level	A bond is stable when there are eight electrons in the most outer energy level of each atom.	"The last energy level is full and then it [the bond] is stable. Similar to Noble gases."
Space	Distance	The energy of the system relates to the distance between the atoms.	You need to invest energy in order to separate them [the atoms]. Each one [atom] has its own energy… so they won't go back together.

Frequencies of the Knowledge-elements

The frequency of each knowledge-element in the pre- and post-interviews is shown in Figure 3. Herein we describe the comparison of the pre-post frequencies in three levels.

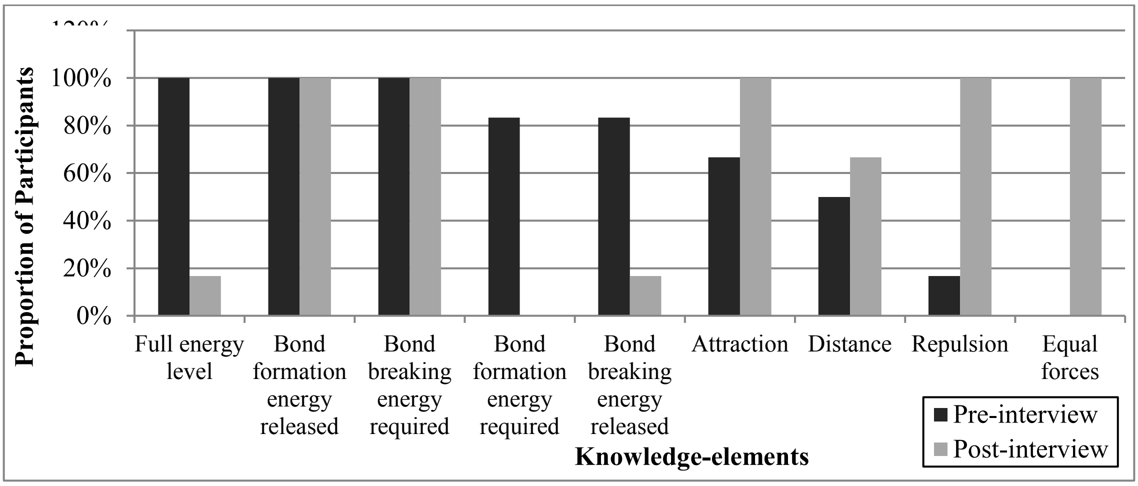

Figure 3. Proportion of students (N=6) mentioning each knowledge-element

Frequency of each knowledge-element. In the pre-interview all students referred to the 'octet rule', meaning they explained stability as having eight electrons in the outer energy level. When asked about energy changes, all students mentioned the correct knowledge-elements of when energy was released or absorbed; most of them (83%) also used the incorrect knowledge-elements. It is important to note that all students could not explain the correct knowledge-element of 'bond formation -energy released' while some intuitively explained that energy is required for bond formation in order to bring the atoms together. Fewer students (67%) mentioned attraction and only one student (17%) mentioned repulsion; none described stability as equal forces. Half of the students referred to the distance between atoms when describing the "need" to approach or separate atoms from each other, indicating they did not relate between distance and *energy*. The frequencies in the post-interview are completely different: all the students mentioned both attraction and repulsion forces, using the force-based explanation to describe stability. All of them mentioned only the correct energy knowledge-elements and only one student (17%) still thought that energy is released while bond breaking.

Mental Models. To obtain the students' overall model, visual clustering was conducted. Rows (student) and columns (knowledge-element) of the pre-interview results were arranged by descending use (bottom to top, left to right) (Figure 4). The post-interview results are presented in the same order, for comparison (Figure 5). From pre- to post-interview we see a significant shift in the group pattern; deserting the ideas of a 'full energy level' and the incorrect energetics, while gaining mainly an understanding of repulsion forces and the balance with attraction. Understanding the bond as equilibrium of forces enabled clarity and consistency in understanding its energetics.

ID	*Full energy level	Bond formation energy released	Bond breaking energy required	*Bond formation energy required	*Bond breaking energy released	Attraction	Distance	Repulsion	Equal forces
St1	1	1	1	0	0	1	0	1	0
St2	1	1	1	1	1	0	0	0	0
St3	1	1	1	1	1	0	1	0	0
St4	1	1	1	1	1	1	0	0	0
St5	1	1	1	1	1	1	1	0	0
St6	1	1	1	1	1	1	1	0	0
Sum	**6**	**6**	**6**	**5**	**5**	**4**	**3**	**1**	**0**
%	**100%**	**100%**	**100%**	**83%**	**83%**	**67%**	**50%**	**17%**	**0%**

Figure 4. Pre-interview knowledge-elements by weight. *Incorrect elements

ID	*Full energy level	Bond formation energy released	Bond breaking energy required	*Bond formation energy required	*Bond breaking energy released	Attraction	Distance	Repulsion	Equal forces
St5	0	1	1	0	0	1	1	1	1
St1	0	1	1	0	0	1	1	1	1
St2	0	1	1	0	0	1	1	1	1
St4	1	1	1	0	0	1	1	1	1
St3	0	1	1	0	1	1	0	1	1
St6	0	1	1	0	0	1	0	1	1
Sum	**1**	**6**	**6**	**0**	**1**	**6**	**4**	**6**	**6**
%	**17%**	**100%**	**100%**	**0%**	**17%**	**100%**	**67%**	**100%**	**100%**

Figure 5. Pre to post shift in students' knowledge-elements and mental models

Correlations between knowledge-elements. To obtain correlations, columns were compared. (1) Octet and Forces (Table 1) are inversely-related: in the pre-interview all students used 'full energy level' knowledge-element and none used the 'equal forces'. In the post-interview the correlation is also inversed but flipped, indicating students used either the octet-based explanation (pre-interview) or the force-based explanation (post-interview). The 'full energy level' is also inversely-related to repulsion knowledge-element indicating that once students became aware of repulsion they built upon it the 'equal forces' knowledge-element and dismissed the octet-based explanation. (2) Distance and Energy are not correlated: in both pre- and post-interview four students referred to space while mentioning both correct and incorrect energy knowledge-elements, indicating that students do not understand the important relationships between potential-energy and distance. (3) Forces and Energy-incorrect are inversed: While in the pre-interview none of the students used the force knowledge-elements but all mentioned the incorrect energy knowledge-elements, in the post-interview all students used the force knowledge-elements without mentioning the incorrect energy knowledge-elements. This indicates that when students understand the underlying principles this confusion decreases. (4) Octet and Energy-correct are not correlated: All students mentioned the correct energy knowledge-elements in both pre- and post-interview whether they used the octet-based explanation or the force-based explanation, indicating that students did not relate energy to forces. However, while in the pre-interview they could not explain their responses, in the post-interview they used the force-based explanations,

> "When a bond is formed, the process is spontaneous. Because attraction forces attract in a way that you don't need to invest energy in them."

Conclusions

Our findings show that students' explanations of chemical bonding and its energetics can be described using four dimensions: Octet-based explanation, force-based explanation, space and energy. Before the intervention students did not refer to force-based explanations; their responses related to energy changes were confused and inconsistent and they used the octet-based explanation when explaining chemical stability.

Learning with the ELI-Chem environment provided students the vocabulary, concepts, principles and analogical sensorimotor schemes that are required to shift from an octet-based explanation to a more force-based explanation. From inconsistency and rote articulations they moved to coherent explanation-based reasoning. They explained chemical stability as a dynamic balance between attraction and repulsion forces, they described correctly that bond formation is due to attraction forces and is associated with release of energy, and that bond breaking requires energy in order to overcome the balance between attraction and repulsion forces. Having the words, sensorimotor schemes, and powerful tools for explanatory force-based reasoning, students constructed a more systematic relationship between concepts they previously held but did not connect.

Acknowledgements

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