# Attraction vs. Repulsion – Learning about Chemical Bonding with the ELI-Chem Simulation

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## Abstract

This work seeks to develop and explore conceptual understanding regarding chemical bonding. Our ELI-Chem environment enables interaction with atoms while experiencing attraction and repulsion forces. The theoretical framework is based on embodied cognition theory by relating conceptual learning to intuition development through repeated and varied bodily experiences. The study uses qualitative methods with 14 high-school students in a pretest-intervention-posttest design, capturing students' gestures and articulations. Our findings indicate a shift from a naïve perception of chemical bonds as stationary solid spheres that keep together like magnets to a more scientific understanding that involves the balance of attraction and repulsion forces, describing the atoms as constantly moving around a dynamic equilibrium.

**Keywords:** Chemical bonding, Attraction /Repulsion forces, Intuition, Embodied learning.

## Introduction

This work seeks to solve one of the basic problems in teaching about matter: understanding the chemical bond as dynamic equilibrium between attraction and repulsion forces. This abstract and non-intuitive topic is difficult to grasp as there are no examples or analogues from everyday life of both attractions and repulsions happening simultaneously. Therefore, we designed and developed a simulation-based learning environment that supports the student's embodied interaction as an atom with another atom and displays the involved forces and energy. In the current study, we examine how conceptual learning results from these interactions; however, the broader framework engages with intuitions as well. The working hypothesis is that learning chemistry based upon a simple set of electrostatic interactions provides a strong basis for understanding several phenomena such as phases of matter (Langhebeheim & Levy, 2016) or chemical structure and reaction energy (Nahum-Levy et al., 2007). Experiencing such interactions physically removes some of the abstraction and makes such understanding deeper and more accessible to many more learners.

## Theoretical Background

Chemical bonding is a fundamental concept in high-school chemistry (Dhindsa & Treagust, 2014; Nahum-Levy et al., 2007; Taber & Coll, 2002). Since concepts related to the molecular level are inherently abstract and outside of normal experience, students learn about chemical interactions without an intuitive basis that can be derived from their experience of the world (Özmen, 2013; Taber & García-Franco, 2010). As a result, they construct naïve models of molecules, usually viewing atoms as solid balls that are stuck together.

In addition, normal teaching often misleads by: presenting chemical bonds as different categories (e.g. ionic, covalent) without relating to the shared principles underlying all bonding (Nahum-Levy et al., 2007); explaining chemical stability of molecular structures using the 'octet rule' heuristic (i.e. with eight electrons in the outer shells) rather than the more fundamental balance between electrostatic attractions and repulsions (Taber, 2014).

The main conjecture of this project is that helping students create and develop *intuitions* regarding forces at the molecular level would make bonding more accessible and understandable. Grounding basic concepts in intuition could help students comprehend and later compound these intuitions into scientific explanations of more sophisticated concepts (Clement, Brown, & Zietsman 1989; diSessa, 1993; Núñez, Edwards, & Matos, 1999; Sherin, 2006) such as molecular structure or energy of chemical reactions. Fischbein (1987) suggests this can be done by creating didactical situations that require personal and experiential involvement. We narrow Fischbein's definition of "involvement" to physical experiences based on *embodied cognition* learning theory (Abrahamson & Lindgren, 2014; Barsalou, 1999; Lakoff & Johnson, 1980). This theory maintains that everyday bodily experience, which underlies intuition, is mapped onto more abstract domains and thus supports *conceptual learning* (Anderson, 2003; Barsalou, 1999; Johnson, 1987; Lakoff & Johnson, 1980).

## The Learning Environment

The ELI-Chem (Embodied Learning Interactive Chemistry v1, Zohar & Levy, 2015) environment was designed to support the development of new sensory-motor schemas by offering gesture control as part of a molecular simulation. ELI-Chem makes the molecular level perceptually accessible and physically manipulable, and is geared to enhance conceptual understanding of the common underlying principles of bonding and interactions.

The ELI-Chem environment enables sensory-motor interactions with atoms as they come closer and further away (Figure 1). It was created with NetLogo (Wilensky, 1999). Students select an atom, drag it across the screen closer and further away from another atom and experience the resulting forces and energy. The mathematical model of the simulation is based on the Lennard-Jones potential for two neutral atoms (Jones, 1924) approximating the electrostatic forces between them. This model consists of two components: a steep repulsive term at short ranges and a smoother attractive term at slightly longer ranges.

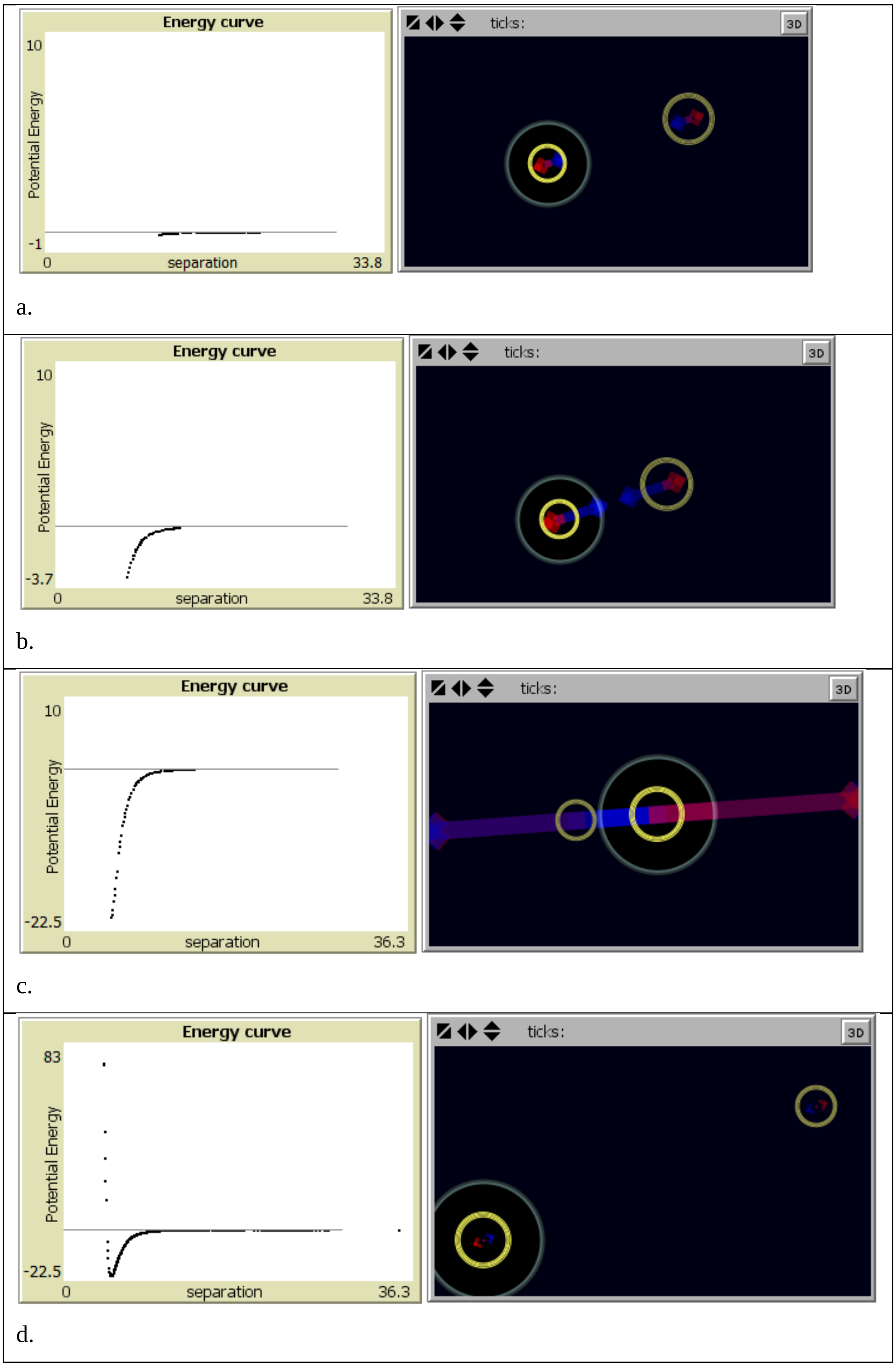


**Figure 1. a) Atoms are far apart; energy is zero. b) Atoms getting closer; attractive forces increase and energy decreases. c) At bond length attractive forces equal repulsive forces; energy is at its minimum. d) When atoms are even closer the repulsion forces dominate.**

## Methods

*Approach*: The study employs a qualitative approach.

*Participants*: The participants are 14 advanced-level high-school students ($10\text{-}12^{th}$ grade) studying towards chemistry matriculation examinations in Israel. Participants were sampled opportunistically as the activities were voluntary and outside of school hours.

*Design*: The study is framed as a pretest-intervention-posttest design.

*Procedure*: Individual sessions included a 10-minutes pre-interview, a 40-minutes hands-on activity and a 10-minutes post-interview. The hands-on activity includes the computer simulation and an on-line worksheet with instructions, questions and explanations. Main concepts addressed: forming and breaking a chemical bond, repulsive and attractive forces, equilibrium state, chemical stability, potential energy diagram, bond-energy and bond-length.

*Data collection*: The pre-post semi-structured interviews were identical and consisted of the same five questions about chemical bonding. Students' interviews were video-captured. Their activities with the simulation were both screen-captured and video-captured.

*Data analysis*: Students' articulations about chemical bonding were coded for conceptual understanding and their gestures while talking were coded as perceptual-motor understanding.

## Findings

Presentation of results includes students' pre- and post-interview (1) gestures (2) articulations.

### (1) Gestures

Students were asked to verbally describe the chemical bond and what happens when two atoms come close together while gesturing.

*Atoms as a basic entity*: In the pre-interview, most (12/14) students used closed fists to describe atoms (Figure 2. b1, b2). The rest of the students (2/14) used straight joined fingers (Figure 2. C2).

*Static versus Dynamic fists*: One central concept is the dynamic aspect of the chemical bond even in a stable state. In the pre-interview, none of the students showed the atoms in a bond as dynamic. Once the bond is established, the atoms do not move anymore. However, in the post-interview all the students (14/14) shifted to an oscillating motion around an equilibrium distance, moving repeatedly inwards and outwards.

*Distance between fists*: Another central concept is the balance between repulsion and attraction which results in there being an equilibrium distance between atoms, commonly named bond length. In the pre-interview (9/14) students' fists approached until they touched each other and were then set firmly in place. The rest of the students (5/14) showed a very small distance between the atoms. In the post-interview, all students (14/14) kept their fists apart at a distance that is larger than that shown in the pre-interview.

*One versus Many*. An atom can be represented as a single object, as described above. However in reasoning about bonding, it is fruitful to consider the different charged objects in an atom: the electrons that move around the nucleus, which includes neutrons and protons. Only in the post-interview, 4/14 students opened their fists slightly, creating spaces between their fingers, and moved their fingers separately.

*Multiple Representations*. An atom can be represented as a symmetrical ball, but one may be interested in their heading to understand the forces operating on the object. Only in the post-interview, 2/14 students used their fists as atoms, simultaneously using their pointing finger for the forces operating on the atom (Figure 2. a2).

Summarizing these findings, students' enacted perceptual-motor schemes reflect a shift from a static to a dynamic model of bonding at an equilibrium distance that includes repulsion, some including a sense of many objects and some superimposing two representations.

| | |
|---|---|
|  a1 |  a2 |
|  b1 |  b2 |
|  c1 |  c2 |
| Pre-interview gestures:<br>Gestures showing bond as two attached atoms. | Post-interview gestures:<br>Gestures showing bond as two atoms oscillating around equilibrium distance. |

**Figure 2. Gestures before and after working with ELI-Chem.**

### (2) Articulations

During the pre- and post-interview students were asked to describe what a chemical bond is and what a stable bond means, to provide an analogue for bonding from everyday life and to assess how close atoms can approach each other (Table 1).

**Table 1. Pre- Post-Interview articulations**

| Topic | Pre-Interview | | Post-Interview | |
|---|---|---|---|---|
| | **Theme** | **Example** | **Theme** | **Example** |
| Description of chemical bond | Chemical bond involves *only attraction* between atoms. (12/14) | "It is a matter of attraction. The electrons are attracted to the nuclei because the nuclei are positive and the electrons are negative." | Chemical bond involves both attraction and repulsion forces. (12/14) | "Now I understand that a chemical bond is when the attraction and repulsion forces are equal." |
| Repulsive forces | Repulsive forces exist *only* when atoms are very close to each other. (3/14) | "They [the atoms] will approach until both nuclei will simply shove each other because both of them are positive." | The *balance* between the attraction and repulsion forces determines how close the atoms can get. (13/14) | "There is an entity that pulls and an entity that pushes. So the chemical bond is when they are equal. It is the distance of which they are equal. This is the case of the chemical bond." |
| Distance between atoms | There is *no distance* between the bonded atoms, they are attached. (7/14) | "They will be very close to each other. They will stop when they are completely attached. One atom's energy level cannot invade the energy level of another atom." | There is a *distance* between atoms; they cannot be attached to each other. (13/14) | "If there are two atoms there will be a distance between them; if they will come too close to each other they will repel each other." |
| Magnetic attraction as analogy | The chemical bond is like *magnetic attraction*. (7/14) | "It is like a magnet, I think. Like those two things that we had when we were kids. It seems to be that there is no attraction and suddenly there is!" | A *magnet isn't* a good analogy for chemical bonding. (13/14) | "Maybe when you try to approach minus and minus it show the repulsion between the two nuclei, but it doesn't show what happens when there is an attraction **and also** repulsion." |
| Chemical stability | Bonds are formed to *fulfill the 'octet rule'*; this is the most stable state. (12/14) | "The bond is formed because they [the atoms] wish to get a full last energy level. That each of them will have eight (or two in case of Hydrogen); This is the most stable state." | A stable state of a bond is when attraction forces balance repulsion forces. (13/14) | "A chemical bond is a stable state between two atoms or two molecules that attract each other with a force that equals the force that they repel each other." |

## Conclusions

Our findings show that before intervention, students don't consider repulsion forces when reasoning about the chemical bond, a new finding in describing conceptual understanding in chemistry. Learning about chemical bonding with the ELI-Chem environment helps students shift from a naïve perception of bonding to a more scientific understanding. This shift occurs for both sensory-motor perception, as accessed through participants' gestures and conceptual understanding, based on their articulations. Students' gestures changed from static touching fists to oscillating motion around an equilibrium distance. From an explanation based on the 'octet rule' depicting the atoms as static "touching" balls, students turn to consider the role of repulsion forces and the dynamic balance between attraction and repulsion forces between bonding atoms. Moreover, after working with ELI-Chem environment students were able to apply their understandings and explain why their naïve example of magnet isn't a good example for bonding.

## Scholarly Significance

The finding that students do not consider repulsion when reasoning about chemical bonds is a contribution towards the literature on students' understanding of science.

Learning with ELI-Chem overcomes two persistent hurdles in learning about the chemical bond that have been highlighted by several leading chemistry education researchers: (1) chemical bonds result from *attractive and repulsive* electrostatic forces; (2) a chemical bond is most stable when attractive and repulsive forces are equal and energy is minimal. Our environment enables students to experience this abstract and non-intuitive phenomenon of two opposed forces acting simultaneously between atoms and explore how the balance between them affects the energy of the system. In particular, it enables students to grasp the existence of repulsive forces and better understand the concepts of dynamic equilibrium, bond-length and bond energy. The study also contributes towards the development of learning theory by incorporating intuitions and sensory-motor knowledge in frameworks that describe conceptual learning.

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