Gamifying intermolecular forces: Improving student performance outcomes for college freshman-level intermolecular forces

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Abstract

Applying concepts for intermolecular interactions (IMFs) is both important and challenging for undergraduates in chemistry-related courses. A card-discard game comparing small molecules was designed to encourage collaboration and peer-led discussion of IMFs. Learning outcomes were analyzed using a pre-/post-activity test. There is overall significant improvement ($p < 0.001$) in test responses, notably a 10.6% ($p = 0.0015$) increase in correct responses to question 6 which requires critical thinking skills. The improvement in learning outcomes suggests significant learning benefits to incorporating the game into an introductory course discussing IMFs.

Introduction

A significant portion of chemistry, biology, and engineering is devoted to the study of molecules and their interactions.[1–3] Understanding intermolecular interactions (IMFs) is important in reaction selectivity and behavior of mixtures in the following domains: synthetic inorganic/organic chemistry, analytical physical chemistry, chemical engineering and food science. Table 1 summarizes some of the concepts students are required to grasp before moving on to the above topics.[3] We focus on boiling points at one atmosphere, as one of the most fundamental physical properties related to IMFs.

Students often have difficulty quickly applying the IMF concepts, especially trend exceptions. For example, students are typically able to state that strong London Dispersion Forces (LDFs) cause a "large" molecule to have a higher boiling point than a "small" molecule, and that for similar sized molecules, one containing hydrogen bonding (H-bonding) will have a higher boiling point than one with only LDFs. However, they are often unable to reason that a large molecule with high LDFs may have a higher boiling point than a small molecule with weak H-bonding.

A sense of scale about the strengths of the intermolecular interactions could improve students' ability to apply concepts of IMFs to reasoning about the relative boiling points of different molecules. This sense of scale can be achieved through interactive exposure to a selection of boiling points of various pure substances and encouraging discussions about IMFs, through a 3-player card game.

Design Principles for Chemistry-based Games

To ensure chemistry discussion is the central mechanic of the game, the design principles are notably similar to and different from other chemistry games.[4–7]

- (I) Base the game on tangible observables. This will increase ease of discussions compared to more abstract chemistry concepts.

- (II) Facilitating discussion through curating a careful selection of a variety of species whose chemistry can be quickly grasped by the students.[5]

Table 1: Concepts about "intermolecular forces" ("IMFs") at a college freshman level[3]

Features present in a molecule:	Interactions present between molecules:	Relative boiling points:	Strength of interaction:
H-bond donors† and H-bond acceptors‡	H-bonding Dipole-dipole LDFs	The highest boiling points of molecular solids, with exceptions	Having more pairs of H-bond donors and acceptors cause stronger H-bond interactions and higher boiling points, with exceptions
A permanent dipole (bond dipoles do not cancel each other), making the molecule a polar molecule	Dipole-dipole LDFs	Boiling points higher than non-polar molecules, and lower than molecules with H-bonding, with exceptions	Having stronger molecular dipoles cause stronger dipole-dipole interactions and higher boiling points, with exceptions
None of the above, making the molecule a non-polar molecule	LDFs	The lowest boiling points of molecular solids, with exceptions	Having more (polarizable) electrons causes stronger LDF interaction and higher boiling points, with exceptions.

Shorthands used: London Dispersion Forces(LDFs), Hydrogen bonding(H-bonding), Permanent dipole- permanent dipole interaction(Dipole-dipole)

† hydrogens bonded to nitrogen, oxygen or fluorine
‡ lone pairs on nitrogen, oxygen or fluorine

- (III) The rules in the game should include straightforward chemistry that can be discussed,[6] instead of memorizing external references or answer keys.[7] Requiring answer keys may shut down discussions.[5] Effective discussions require that students have been introduced to this chemistry beforehand, through lecture or otherwise.
- (IV) Give students direct control/options over game difficulty. Having a fixed difficulty level may leave some students behind while not challenging others.
- (V) Have strategic elements in the game. There should be penalties and consequences for mistakes and risks to encourage students to flesh out their thought process.[7] There is a need to not demoralize students,[4,5] but careful design of these consequences is possible.

Game Description

The game type selected was a card-discard game - the students start with 7 cards each. To win the game, a student must be the first to discard all of their cards. Each card represents a molecule and includes the name, the chemical formula, boiling point, and the Lewis structure drawn to show geometry. The boiling points were included to fulfill design principle (I). The 36 cards (Table 2), contain 30 different molecules, including the main group hydrides, diatomics, typical VSEPR examples and chloro-methanes, all with a single "central" atom.

As part of design principle (II), these molecules have a reasonable range of VSEPR and Lewis structures that can be easily interpreted by the students. The 30 molecules were selected specifically to avoid more complicated interactions (for example, significant zwitterion formation).

The game was designed for three players to encourage discussion within this small group. A turn of the game involves two players passing a card of their choosing from their hand to the third student who acts as an arbiter. As an ice-breaker to start discussion, the first arbiter

Table 2: Molecules and boiling points used in the IMF challenge

Molecule	Number of cards	Boiling Point(K)
HF	1	293
HCl	1	188
HBr	1	206
HI	1	238
H_2O	3	373
H_2S	1	213
H_2Se	1	232
NH_3	3	240
PH_3	1	186
H_2	1	20
N_2	1	77
O_2	2	90
F_2	2	85
Cl_2	1	239
Br_2	1	332
I_2	1	457
PCl_3	1	349
PCl_5	1	440
SF_4	1	235
SF_6	1	222
$SOCl_2$	1	348
OCH_2	1	254
CO_2	1	217
HCN	1	299
CH_3Cl	1	249
CH_2Cl_2	1	313
$CHCl_3$	1	334
CCl_4	1	350

is the person with the most recent birthday. If possible, the arbiter selects a reasonable IMF comparison (which card has stronger LDFs, for example) for the two cards. The arbiter can ask for replacement cards if there is no acceptable comparison. The arbiter then places the two cards in front of the players and announces the comparison. The non-arbiter players race to tap the correct card. Both cards are discarded. Tapping the correct card first allows the player to discard an additional card, while tapping the wrong card results in drawing a card. The player to the left of the arbiter becomes the next arbiter, and a new turn starts.

Design principle (III) and (IV) are fulfilled - discussing the answer is required if an answer key is not given, and the arbiter can control the difficulty of the activity. Design principle (V) is fulfilled by the race to tap and the rules for card drawing/discarding based on correctness.

While the boiling point given on the cards may assist the students in discussion, the boiling points may also help build a sense of scale about the different IMFs. In particular, some cases promote critical thinking surrounding trends beyond pattern recognition.

Two days after a lecture on IMFs, a class was introduced to the game, which took 15 minutes. Groups were provided one set of cards, and each student received a rule sheet and a worksheet. They were given 20 minutes to play.

The for-credit worksheet was used to promote active engagement. This has been shown to improve outcomes in classes largely comprised of non-major students with low motivation.[8] The worksheet instructs the arbiter of each turn to record the Lewis and VSEPR structure of the cards played, the IMF comparison chosen and the correct card. The design of the worksheet was not evaluated in this study to avoid reducing the n-values by introducing more variables.

Evaluation

IRB approval for studies in the professor's classes is obtained and a study information sheet was posted. Students were reminded of this posting as a part of the pre-activity lecture. The pre-/post-activity test (see supporting information) consists of 6, 4-option multiple choice questions and the student's student ID number, allowing the use of the two-tailed paired t-test in evaluating the significance of the results. Students were given 5 minutes to respond to the test immediately before the activity(after the pre-activity lecture) and immediately after the activity.

Accurate Lewis and VSEPR structures were shown to isolate the topic to IMFs. The molecules chosen for the test are not part of the 30 molecules used in the card game. While some of these molecules have more complicated intermolecular interactions, the questions were designed to be answered at the freshman level.

The student's average score on the test improved from 3.48/6 (σ^2 = 2.41) to 3.97/6 (σ^2 = 2.35) after the activity ($p < 0.001$). Figure 1 shows the breakdown by question.

Question 1 had the number of correct responses increased significantly from 69.1% to 83.5% ($p < 0.001$). These students were better able to recognize the stronger LDFs in neon compared to helium after the activity.

Question 2 had the number of correct responses increased non-significantly from 60.6% to 61.9% ($p = 0.70$). After the activity, students were not significantly better or worse at recognizing that methylimine is "capable" of hydrogen bonding as a cause for its higher boiling point compared to ethene. Methylimine was picked as a "unseen" molecule since typical questions do not include unstable molecules. This suggests that the other significant results after the activity are caused by the activity itself, and also suggests the importance of presenting a range of desired functional groups in the classroom for the understanding of IMFs.

Question 3 had the number of correct responses increased non-significantly from 63.1% to 67.4% ($p = 0.22$). After the activity, students were not significantly better or worse at recognizing that the *cis-* isomer of dichloro-difluroxenon has stronger dipole-dipole interactions than the *trans-* isomer. This suggests that the game would be better if it included more molecular geometries.

In contrast, Question 4 had the number of correct responses increased significantly from 55.1% to 66.1% ($p = 0.0020$). After the activity, these students were significantly better at recognizing that the *cis*- isomer of dichloro-ethene has stronger dipole-dipole interactions than the *trans*- isomer, which would imply that even with the limited number of molecular geometries, students were able to improve in this concept. It is unexpected, given question 3 and 4 test similar principles, that improvement would be seen on only question 4. Further development of a deeper analytical instrument would be required to elucidate this difference.

Question 5 had the number of correct responses increased significantly from 69.1% to 76.3% ($p = 0.0029$). After the activity, these students are significantly better at recognising that glycerol has more hydrogen bonding than pentanol as a cause for glycerol having the higher boiling point. This is unexpected given that no alcohols are present in the card game, and the result for question 2. The data could be confounded by the students being given the same time limit to answer all 6 questions. Being exposed to these molecular geometries through other resources might also be a factor.

Question 6 had the number of correct responses increased significantly from 30.9% to 41.5% ($p = 0.0015$). After the activity, students are significantly better at recognising that sulfur trioxide does not have dipole-dipole interactions, but has significantly stronger LDFs when compared to sulfur dioxide's weaker LDFs and dipole-dipole interaction, as a cause for sulfur trioxide having the higher boiling point. Sulfur trioxide forms dative bonds with itself, and thus is another "unseen" molecule. Question 6 is by far the question with the poorest performance, supporting the discussion in the introduction. However, the significance of improvement rivals question 1. Given the results of the other questions, this demonstrates that the game is useful for developing critical thinking skills in these students without hindering their ability to recognise simple trends.

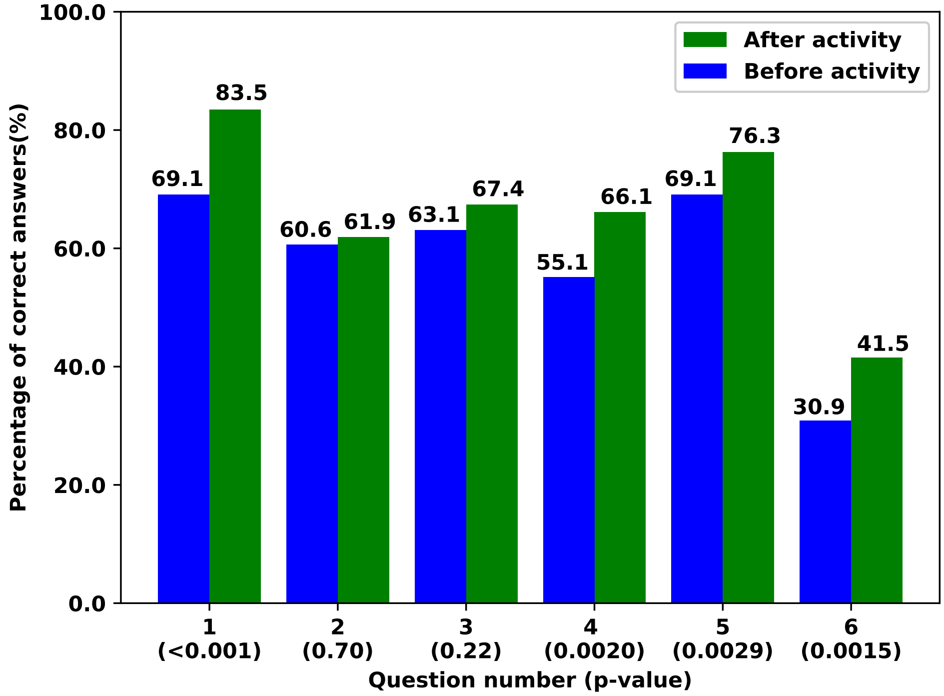

Figure 1: Percentage of correct answers from 236 matched responses (two-tailed paired t-test p-values in parentheses)

Limitations of the study

To keep the card game focused, only molecular compounds are included. A different set of molecules would be required for focusing on ionic or metal-ligand interactions. Due to limitations determining an appropriate control group, longitudinal knowledge and application retention were not tested.

Conclusions

The design objective for the IMF game discussed here has been met. Given only 20 minutes of gameplay, the students improved on several of the tested outcomes compared to an active learning lecture. It is important to note that this game should be integrated into a larger lesson on IMFs and is not meant to be a stand-alone introduction. Though this particular trial was on a limited set of cards, further iterations of the game could be played with other card choices aimed to improve other IMF learning outcomes not discussed in this targeted trial.

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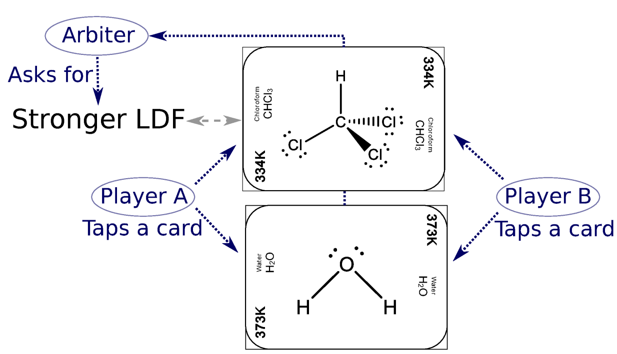

Figure 2: "For Table of Contents Only"

A card game for improving learning outcomes for intermolecular forces at the college freshman level.