Use of virtual environments to improve Physics learning: report from a case study

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Summary

Students who are mostly visual-spatial learners (*i.e.*, who prefer to understand the world through their eyes and to express their ideas through graphical arts) may dislike traditional Physics classes because of its overemphasis on lecturing, rote memorization, and drill and practice exercises. It is clear that these and other students should be involved in their learning more than simply listening to lectures or reading textbooks.

Advances in computer technology have lead to various high-quality educational tools including interactive programs, multimedia presentations and, more recently, virtual reality. Virtual reality is a computer interface characterized by a high degree of immersion and interaction, making the user believe that he is actually inside the artificial environment.

We have built a virtual environment – *Virtual Water* – to support the learning of some concepts of Physics and Chemistry at the final high school and first year university levels. It is centered in the microscopic structure of water and explores concepts related to phases of matter and phase transitions. We have carried out a qualitative study with first year students of Physics, Chemistry, Industrial Chemistry, Physics Engineering and Civil Engineering courses of the University of Coimbra, Portugal. Being asked before the use of our software to describe their views on phases and phase transitions, students revealed some misunderstandings which are common in the pedagogical literature. We have tried to overcome them by making students to explore the virtual environment with the aid of a script. We concluded that graphics visualization tools with three-dimensional animations were useful to increase the understanding of phase transitions, although no much value was added to the understanding of the phases themselves.

Keywords: virtual reality, virtual environment, water, phases, phase transitions

The importance of visualization

The scientific language, including scientific concepts and the relationship between them, differs from the language of everyday life and therefore it is to be expected that students experience difficulties in understanding it. The use of images is referred by several authors [Tos87, Bar89] as a powerful means to smooth the approach to scientific concepts. From simple schemes to the color pictures that illustrate modern textbooks, there are several forms to transmit scientific content in a visual way. With adequate images students may visualize some abstract concepts, allowing for a more "direct" contact with the subject being studied [Bod88].

Various authors [She82, Tre85, Kos94, TP94] defend the regular use of computational simulation and visualization tools in Physics and Chemistry teaching. They argue that students should be given an active role in the use of these tools [Kha01a, Kha01b, Maz97]. Some good classroom practices are known at the secondary [Jon99] and university levels (www.umich.edu/~chem215).

Thermodynamics is a good subject for using animated pictures to visualize processes, as, for instance, the motions that occur at microscopic level in the gaseous and liquid phases of water. For example, the *Molecular Dynamics* program developed by *Stark Design* (www.starkdesign.com) (Figure 1) simulates the behavior of rare gases (helium, neon, argon and krypton) in three and two dimensions. It is possible to associate to each atom the respective velocity and to follow the effect of temperature and pressure changes in the box where the simulation takes place establishing therefore a relation between particle dynamics and macroscopic behavior.

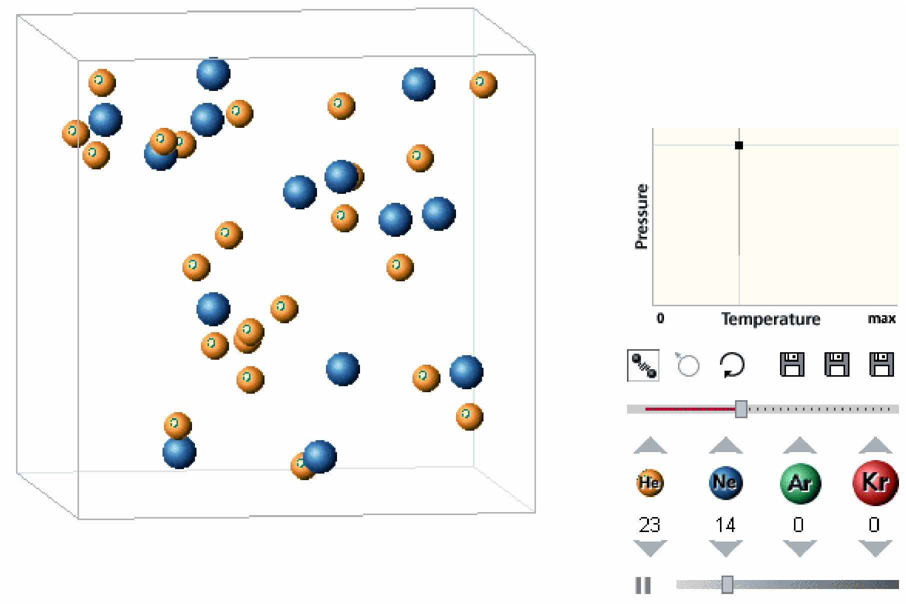

Figure 1: Snapshot of the *Molecular Dynamics* program. The figure shows a 3D simulation of a mixture of 23 helium atoms with 14 neon atoms. The control buttons on the right allow for choosing the number and type of atoms, the temperature variation, the interatomic potential and the simulation speed.

Difficulties in Thermodynamics learning: phases and phase transitions

The microscopic structure and the behaviour of matter, in their different states of aggregation, is a subject in which students usually have unclear conceptions [GSH87]. A possible explanation for this problem is the fact that experimental data come from macroscopic observations while the explanatory theories are based on the properties of atoms and molecules, an invisible world which has, in large measure, to be imagined.

In Physics and Chemistry one has to consider the macroscopic and microscopic worlds and to be able to alternate between them (sometimes we have to take the two simultaneously). This is not easily achieved by students. In effect, a study done by A. Griffiths and K. Preston

[GP92] with Canadian students at the last high school kevel showed that students tend to transfer to the microscopic world some properties observed in the macroscopic world.

Many other works at different learning levels have been made to identify and understand students' wrong ideas in Thermodynamics with respect to phases and phase transitions [OC83, Sta88, And90, BWB93, KWG98]. Table 1 presents a synthesis of some wrong conceptions found by the authors of those works. One may think that computer simulations will be adequate to deal with these cases.

Table 1: Some wrong conceptions in Thermodynamics relative to phases and phase transitions

Concepts	**Wrongs ideas**
Gaseous phase	In the gaseous phase space is all taken by molecules [BWB93, KWG98, BG94].
Solid phase	Molecules are very close to each other so that no empty spaces exist between them. The molecular binding is due to something external [GP92].
Solid, liquid and gaseous phases	Difficulties in distinguishing the several phases [Rya90].
Liquid – solid transition	When the ice is heated up, heat expands each molecule, leading to its separation [GP92].
	In the liquid-solid transition the weight of the sample increases while in the inverse process the weight decreases. Hydrogen and oxygen combine to form water [OC83, BT91].
Liquid – gas transition	When water boils the bubbles are made up of oxygen or hydrogen [OC83, BT91].
Speed of molecules	The speed of a molecule is determined by its size. The more space a molecule has to move around the larger its velocity will be [GP92].
Temperature	Molecules are hot or cold according to their phases [BBD84, GP92].
Molecular dynamics	The spacing between the particles is small in the gaseous phase [BWB93].
	Students feel difficulties to foresee the molecular behavior in the various phases [BES86, CH78, GSH87, Yar85, WA95].
Shapes of molecules	Particles have different forms in the different states: gas molecules are round, liquid molecules have irregular forms, and solid molecules are small cubes [HA91, GP92, KWG98].
Size of molecules	The diameter of the molecules decreases progressively in the successive transitions from solid first to liquid and then to gas [DAW78, GP92].
Weight	The weight of a substance changes in phase transitions [KWG98].

We would like to highlight the following two works done with university students:

- The study by C. Ryan [Rya90] with American Physics and Chemistry students, whose goal was to analyze whether they knew how to characterize and distinguish the different phases of matter. He verified that students tended to classify phases as a function of the sizes of the constituent particles.

- The work by D. Benson, M. Wittrock and M. Baur [BWB93], with many American Physics, Chemistry and Biology freshmen, whose conclusion was that students understand gas as a continuum which shows a behavior very similar to that of a liquid.

Virtual reality

Up to now the use of computational means in Physics Education stood mainly on the creation of 2D representations. However, recent technological advances have created new possibilities and the visualization of 3D objects and data became increasingly important in learning several scientific subjects. It is possible that the change from 2D to 3D helps to increase the understanding of processes which take place in full space. One of the most promising means of teaching and learning science is virtual reality, a technique where users feel virtual scenarios as being real. Virtual reality is a computer interface characterized by a high degree of immersion and interaction, making the user believe that he is actually *inside* the artificial environment. In a perfect virtual environment, a user would be completely unable to determine whether he is experiencing a computer simulation or the “real thing”. Virtual environments, based on 3D graphics, may facilitate the formation of conceptual models since they provide the capabilities to develop applications addressing higher skills.

Although the concept of virtual reality has been around for more than thirty years, only recent progress in hardware and software brought this technology to within the reach of ordinary researchers and users.

The main strength of virtual reality is its ability to visualize situations that cannot be seen otherwise and, moreover, to immerse learners in them. For example: a photo or movie may show students the internal structure of ice, but only virtual reality allows them to “enter” inside and observe it from any viewpoint; or an animation can illustrate the solid-liquid phase transition, but virtual reality provides students with a much stronger sense of "being there".

Virtual Water

We have developed *Virtual Water* to support the learning of some concepts of Physics and Chemistry by students who are at the final year of high school and first year of university. Our virtual environment is centered in the microscopic structure of water and, among others subjects, explores concepts related to phases of matter and phase transitions.

For designing the *Virtual Water* models we used the free software *PC Gamess* [Gam], that performs the calculations on the water molecule, and *Molden* [Mol], for the molecular representations. For model development and optimisation we used commercial software packages (*Mathcad* and *3D Studio Max*) and for implementing the molecular dynamics algorithm *Visual C*$^{++}$. Concerning the definition and creation of the virtual scenarios we used *WorldToolkit* (from Sense8).

The minimal hardware requirements for *Virtual Water* utilization are a Pentium III processor, 128 MB of RAM, 150 MB of free hard disc, graphics board accelerator, and Microsoft Windows NT 4.0 or higher.

Using *Virtual Water* we studied some wrong conceptions of students about the molecular dynamics of water and analysed the utility of our program to overcome them. We have carried out a qualitative study with 20 first year students who were attending the first year of Physics, Chemistry, Industrial Chemistry, Physics Engineering and Civil Engineering courses at the University of Coimbra, Portugal.

We present below a short characterization of the various sceneries of molecular dynamics, the questions we have asked to the students in our study before and after software exploration, some representative answers and a selection of their free comments.

Molecular dynamics

These sceneries focus on the molecular simulation of water dynamics in the gas, liquid and solid phases. A 3D box with 72 molecules is displayed. Phase transitions occur upon change the temperature or the pressure. It is always possible to move through the virtual environment and to visualize the contents of the box from any point.

Gaseous and liquid phases and gas-liquid phase transition

It is clear from our virtual environment that, in any phase of water, empty intermolecular spaces are present, these being smaller in the liquid phase than in the gas phase. The density is, therefore, different in these two phases.

Gaseous phase

In this scenery we see 3D animations of molecular dynamics, which correspond to a temperature slightly above 100 ºC and atmospheric pressure (Figure 2). The most relevant behaviours of the water molecules are their higher mobility and the difficulty for forming intermolecular bonds.

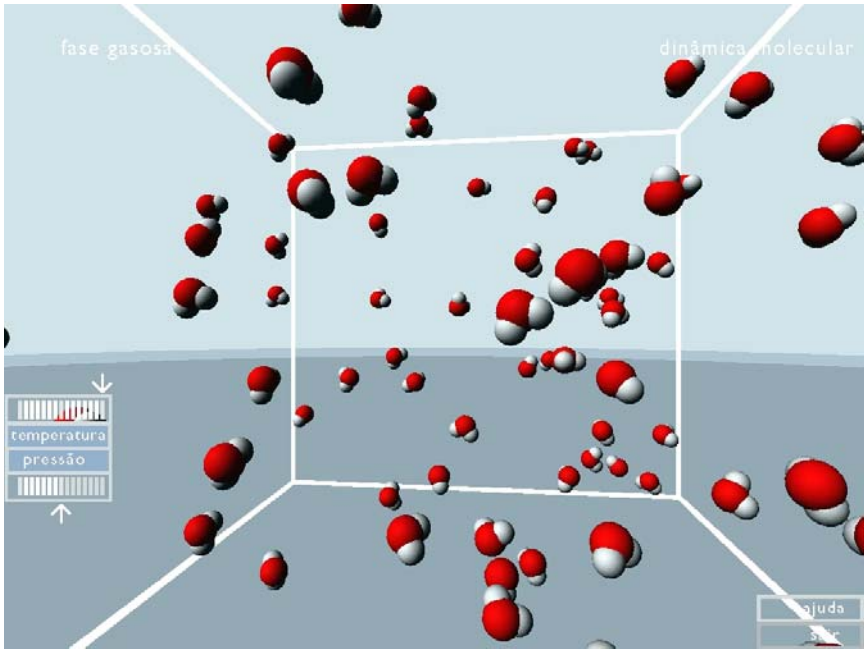

Figure 2: Gaseous phase slightly above 100 ºC and at atmospheric pressure. The molecules have a very high mobility.

A question on the gas phase we have raised and some student's answers before and after software use are the following.

Question 1: Why is the volume occupied by the molecules so large?

	before software use	After software use
Answer 1	"*It is like having a gas in a balloon. The molecules have a lot of energy and move without restrictions*".	"*Because (...) if the temperature is higher then the molecules tend to spread*".
Answer 2	"*Because nothing hinders the motion of molecules. There are no forces and particles move with maximal energy*".	"*Because the temperature is maximal for constant pressure. The molecules received more energy*".

Gas-liquid transition

By decreasing the temperature at constant pressure the molecules form intermolecular bonds and loose their mobility (Figure 3). We notice a density increase and view some molecules clustering together.

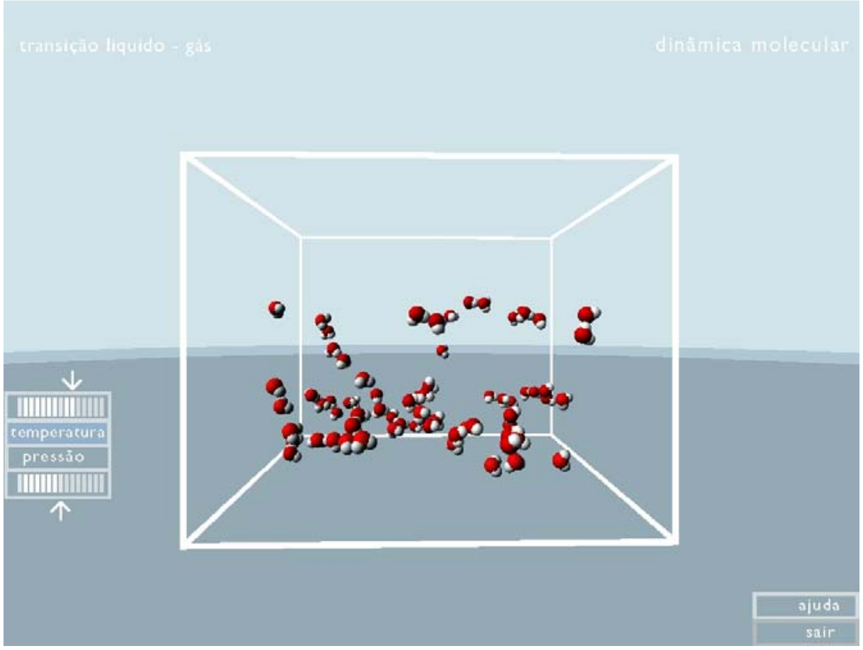

Figura 3: Gas–liquid transition: the most relevant phenomena are the decrease of molecular mobility, the formation of intermolecular bonds and the density increase.

A question and some student's answers on the gas-liquid transition are as follows.

Question 2: Is there any change of the molecules?

	before software use	after software use
Answer 1	"*They become larger*".	"*The molecules do not change but their speed changes*".
Answer 2	"*The molecules are the same but now, with the increase of pressure, they tend to increase its size*".	"*They look the same but now are more close*".

Liquid phase

If we continue to lower the temperature but keep the pressure constant we obtain the liquid phase (Figure 4). The phenomena which have been observed in the latter phase transition intensify now, leading to a larger number of intermolecular bonds, smaller mobility and larger density.

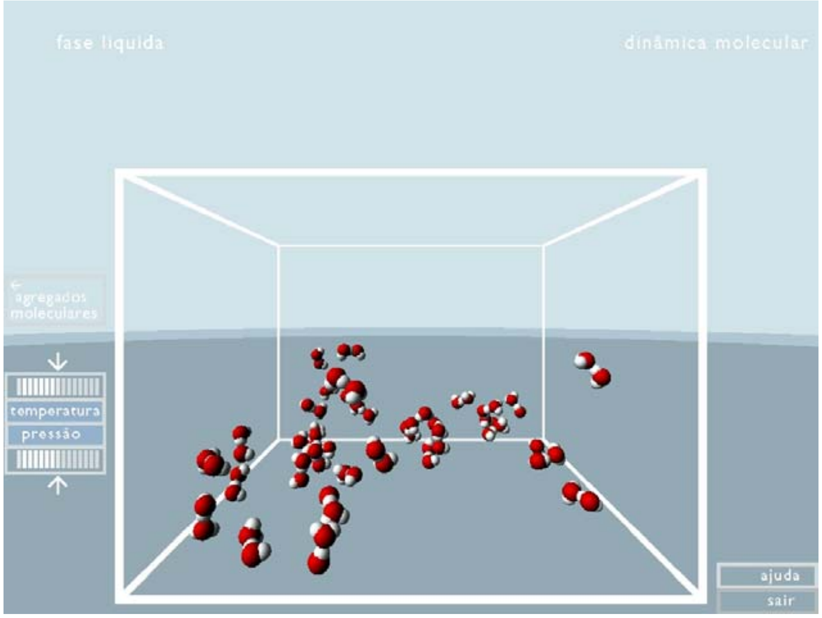

Figure 4: Liquid phase: Intermolecular bonds are formed, the molecular mobility is reduced and the density increases.

Again, we have asked students about this phase before and after careful visualization.

Question 3: Was there any change in the weight of the molecules?

	before software use	after software use
Answer 1	"*Yes. They are losing speed and also become larger so that they take more space* ".	"*The individual molecules (H_2O) have the same atoms. The weight will be the same. However the $2H_2O$ molecule is heavier*".
Answer 2	"*The weight should increase because they are losing speed and are falling*".	"*The motion of molecules is now slower. But the water molecules remain the same. I think that their weight is the same*".

Liquid-solid transition

If the temperature gets still lower, the mobility of the molecules becomes even smaller and small pieces of ice structures show up (Figure 5).

Figure 5: Liquid–solid transition: There is a loss of mobility of molecular aggregates and new intermolecular bonds arise so that the ice structure emerges.

A question and some students answers before and after view of the liquid-solid transition in the computer are the following.

Question 4: Explain what happens to the density.

	Before software use	After software use
Answer 1	"*The density increases because the weight increases*".	"*The density increases because the molecules are more close*".
Answer 2	"*The molecules join and, since the set is heavier, fall down. The density has therefore to increase*".	"*The density increases. The molecules are now mainly restricted to the bottom of the box*".

Solid phase

The temperature is reduced until 0 ºC, when the hexagonal structure of normal ice (Ih) (Figure 6) appears in its full extension. Molecular motions are now almost absent.

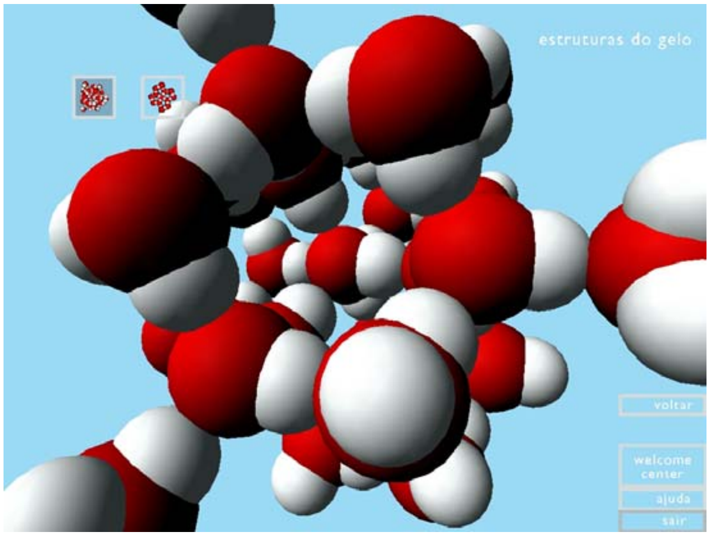

Figure 6: Structure of normal ice. It is a compact structure at large scale with molecular motion almost absent.

A question and some answers relative to the solid phase are the following.

Question 5: Explain the normal structure of ice based on molecular binding.

	before software use	after software use
Answer 1	"*The structure of ice is a pentagon. The heaviest atoms (oxygen) are in the middle and the hydrogen atoms are outside*".	"*The structure is compact forming a large and ordered string. It looks like a hexagon*".
Answer 2	"*Molecules are all compressed forming plane surfaces*".	"*There is a bonding between hydrogens and oxygens. There is a lot of space between atoms*".

We recognize in most of these answers errors which have been identified by other authors. For example, the answers to question 2, about the shape of molecules, correspond to wrongs ideas recognized by Haidar and Abraham [HA91], Griffiths and Preston [GP92], and Krnel, Watson and Glazar [KWG98] (see Table 1).

We have given here only a glimpse of student's answers, indicating that in some cases the conceptual understanding was improved. Our statistical results are described in detail in reference [TFA02]. We may summarize them by saying that our graphics visualization tools with 3D animations have shown to be useful to increase the understanding of phase transitions, although no much value was added to the understanding of the phases themselves. The most important characteristics that contributed to students' conceptual comprehension were the interactivity and 3D perception provided by our virtual environment.

One of the values of virtual reality is its ability to give substance to abstract concepts. This was achieved in our project. As one student said, "*when I work on a physics or chemistry problem for an hour, all I have to show for my efforts is a number, which doesn't always mean anything to me. This program gave me a chance to see water molecules behaviour for the first time*".

Students exposed to our computer environment were in general very enthusiastic. In response to free format questions they said that:

- "*This visualization will stay with me*";
- "*This experience will stay in memory much longer than any notes or lectures*";
- "*Very good form of learning, a good complimentary device*";
- "*The software is especially good for 3-D behaviours*";
- "*It is easier to understand things when you can visualize them*".

Furthermore, students reported an increased motivation for the theory behind molecular dynamics after having explored the 3D molecular motion and its relation to macroscopic properties.

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