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Learning Chemistry by Playing

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Learning Chemistry by Playing

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To my family.

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Always follow your dreams.

Abstract

Chemistry belongs to the STEM fields (science, technology, engineering and mathematics), which are often labelled as hard subjects of matter. This idea is a starting point to demotivate children even before they learn the subject at school. In addition, school subjects are increasingly extensive and common teaching strategies are becoming less captivating.

On the other hand, nowadays children have a strong relationship with technology, particularly with mobile games, which are a good way to pass the time with small effort while providing an enjoyable experience. The evolution of technology also allows us to take advantage of certain tools such as augmented reality, which has presented great potential in the educational field and in the creation of motivation.

Another important subject that is directly related to chemistry is climate change. Taking into account that children are the generation of the future, it is relevant that they are aware of Climate Change causes and the impacts that those changes have and will have in our planet, as well as the solutions and measures to be implemented, so that the effects won't be aggravated.

Hence, we created an educational mobile game targeting 9 to 12-year-old children to explore its utilization in the transmission of chemistry knowledge, as well as in the creation of motivation and in sensitization regarding climate change subjects. The game contains a unique storyline, and it is based on augmented reality technologies and tangible interfaces, that enrich the learning experience.

According to our findings, the game provided a pleasant experience to the users, who significantly improved their knowledge regarding basic chemistry concepts addressed in the game. In addition, the game promoted a more positive attitude regarding the chemistry field and awareness regarding the climate change problematic.

Keywords: Mobile game, augmented reality, tangible interfaces, storytelling, education, chemistry, periodic table, climate change, children, unity

Resumo

A química pertence às áreas STEM (science, technology, engineering and mathematics), que são frequentemente rotuladas como difíceis. Esta ideia é um ponto de partida para criar desmotivação por parte das crianças mesmo antes destas aprenderem a matéria na escola. Para além disso, as matérias escolares são cada vez mais extensas e as estratégias comuns de ensino estão a tornar-se cada vez menos cativantes.

Por outro lado, hoje em dia as crianças têm uma forte ligação com a tecnologia, em particular com os jogos de telemóvel, que são uma boa maneira de passar o tempo com pouco esforço e ao mesmo tempo providenciam uma experiência agradável. A evolução da tecnologia permite-nos também tirar partido de ferramentas como a realidade aumentada, que tem apresentado um grande potencial na área da educação e na criação de motivação.

Outro assunto de grande importância diretamente relacionado com a química são as alterações climáticas. Tendo em conta que as crianças são a geração do futuro, é importante que estas estejam a par das causas e impactos que estas alterações têm e terão no nosso planeta, e ainda das soluções e medidas a serem implementadas, de forma a não agravar os seus efeitos.

Como tal, foi criado um jogo educacional para dispositivos móveis destinado a crianças dos 9 aos 12 anos, pretendendo explorar a sua utilização na transmissão de conhecimentos de química, bem como na criação de motivação e na sensibilização relativamente às alterações climáticas. O jogo contém uma história única, e é baseado em tecnologias de realidade aumentada e interfaces tangíveis, de forma a enriquecer a experiência de aprendizagem.

De acordo com nossas descobertas, o jogo proporcionou uma experiência agradável aos participantes do estudo, que melhoraram significativamente o seu conhecimento em relação a conceitos básicos de química abordados no jogo. Para além disso, o jogo promoveu uma atitude mais positiva relativamente ao tema da química e uma conscientização relativamente à problemática das mudanças climáticas.

Palavras-chave: Jogo de telemóvel, realidade aumentada, interfaces tangíveis, storytelling, educação, química, tabela periódica, alterações climáticas, crianças, unity

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Acronyms

AR Augmented reality

GHG Greenhouse gas

TUI Tangible user interfaces

VFX Visual effects

Chapter 1

Introduction

This chapter introduces the project presenting its motivation as well as a summary of the proposed solution and respective goals. Lastly, it enumerates the main expected contributions and the document organization.

1.1 Motivation

Nowadays, technology is often present in the learning process, mostly through the use of computer programs, and the computer itself has become almost a required resource in this field. However, some of the used strategies to teach subjects such as PowerPoint are becoming less captivating, specially when it comes to children, and the fact that the school subjects are increasingly extensive doesn't help. So, it seems the right time to think about creating a new approach, taking advantage of the growing of technology and its studies.

Unlike portable computers, which are usually heavy and more difficult to move around, mobile phones always go with us anywhere, and in these days mobile phones are often smartphones, with network access, sensors and app stores. This makes possible the use of smartphones as a tool to learn through apps and games, and the learning process can be adapted to each user, respecting each learning speed. Therefore, it is not a surprise that the creation of educational games is growing, presenting effective results in several studies.

Chemistry belongs to the STEM fields (science, technology, engineering and mathematics), which are often labelled as hard subjects of matter. Particularly in chemistry, the difficulty level is often associated with the process of understanding concepts which are abstract and not visible in our daily life [14, 57]. Nevertheless, studies [10, 21, 42,

48, 68] indicate that augmented reality and tangible objects can help to increase knowledge when it comes to those abstract concepts, particularly in understanding atoms and molecules in chemistry. Hence, introducing chemistry concepts to children earlier can help to demystify the idea that they are difficult and motivate them to learn.

Among the chemistry topics, the climate change problematic is an important one. This phenomenon has become significant, whose effects don't pass unnoticed, from small ones visible in our daily life like early flowering and the appearance of mosquitoes in winter to tragedies such as one of the most recent ones - the Australia fires. Climate change has become a major problem, and such information and measures need to be passed to the future of humanity (children). It is also important that those prevention measures are applied by children while still younger, so that it turns into a habit in their daily life. In addition, it is often through children that the message arrives to adults, more precisely to their relatives and/or closest people.

1.2 Goals and Solution

With this dissertation we expect to accomplish the following goals aimed at children from 9 to 12 years old without previous chemistry knowledge:

- **Attitude change regarding the chemistry field** - generate motivation and demystify the idea that chemistry is a hard field
- **Acquired knowledge** - children should retain some knowledge regarding the topics addressed in our game
- **Behaviour regarding the climate change problematic** - sensitize children for the climate change problematic and create a desire to implement small environmental friendly practices in their daily routines

In order to accomplish these goals, we created an educational mobile game that allows players to explore basic chemistry subjects, without feeling like they are actually studying. Furthermore, the game also provides information about the climate change problematic, encouraging the users to act in an environmental friendly matter, taking advantage of the storytelling power for that purpose.

To keep the player motivated, besides creating an interesting gameplay, that aims to shift the focus from the chemistry subjects onto the fun aspects of the game, we decided to utilize appropriate technologies to accomplish that goal. Tangible interfaces allow the integration of the digital with the physical as well as the manipulation of real objects that can be augmented (AR - augmented reality). Since these technologies not only have the potential to represent chemistry abstract concepts, but also contribute for creating an engaging experience, they were the final chosen technologies that we incorporated in our game.

The creation of the game allowed us to explore the utilization of mobile games based on AR and tangible objects and understand their effects in achieving the referred objectives.

1.3 Main contributions

The main contribution of this dissertation is the creation of the chemistry smartphone game that will allow children from 9 to 12 years to enjoy an immerse experience while acquiring some knowledge regarding basic chemistry topics, as well as inform them regarding the climate change problematic, and encourage them to introduce environmental friendly practices in their daily routines.

Other important contribution of this thesis is the study and analysis of the impact that the used technologies and different forms of interaction have in terms of education, motivation, user experience, and awareness for the climate change problematic.

1.4 Document organization

This document was divided in the following chapters:

Chapter 1 - Introduction This chapter presents the motivation of this dissertation and summarizes the proposed solution and its goals. Finally, it enumerates the main contributions.

Chapter 2 - Background and related work Introduces the concepts integrated in the final solution and presents the studies that are relevant for this thesis, as well as the work related with it.

Chapter 3 - Chemistry with a hint of magic Presents a detailed description of the proposed solution.

Chapter 4 - Design process and Implementation Describes the design process that lead to the final solution, by presenting the suggestions, decisions, justifications and improvements made.

Chapter 5 - Evaluation Presents the final testing phase showing our proposed evaluation model and describing our methodology and final results.

Chapter 6 - Conclusions and future work Discusses the results and presents the future work to improve our solution.

In addition to the described chapters, we also included some appendixes that visually support them.

Chapter 2

Background and related work

This chapter presents the concepts that were relevant to create the final solution as well as the study and analysis of work related with the thesis, in terms of subject, technologies and goals.

2.1 Chemistry concepts

Among the different educational chemistry topics, the ones that present more learning challenges require abstract thinking [14, 57]. One example of this is the Periodic Table, since its elements address non observable levels of representation. However, the Periodic Table is a fundamental topic because "it builds up basic knowledge for other sets of understanding in advanced concepts " [57].

Those chemistry abstract concepts, related to the topics of atoms, molecules and the Periodic Table itself, are introduced to Portuguese students in the 7th and 8th grade. Therefore, subsections 2.1.1, 2.1.2 and 2.1.3 present a summary of said topics, based on two portuguese school books [20, 32].

Although our target group does not present previous knowledge in this subject, this research is important so we can introduce them concepts they will learn hereafter in school.

The last subsection 2.1.4 features the climate change problematic.

2.1.1 Atoms

Atoms are really small particles, containing two regions. One of them is the atomic nucleus, where are the protons, which are positive charged particles, and the neutrons, without electrical charge. The other region contains electrons, negatively charged particles that orbit around the nucleus. An atom is electrically neutral, since, in total, it has as

much protons as electrons - their attraction holds the atom together.

The most recent and most accepted model to represent an atom is the so-called Electron Cloud Model, that is illustrated in Figure 2.1. Instead of thinking that the electrons describe orbits around the nucleus, the Electron Cloud Model shows a cloud of electrons, called *atomic cloud* that represents where any electron could be at any time, since they have an enormous speed. The atomic cloud is more dense near the nucleus since it is the most probable area to find the electrons, and less dense far from the nucleus, where the probability is lower.

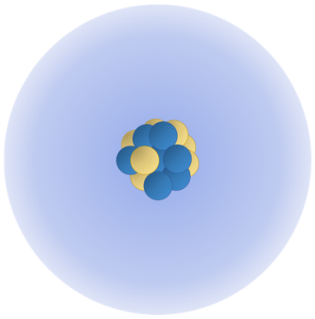


Figure 2.1: Electron Cloud Model[1]

The number of protons (also called the *atomic number* of an atom) determines which element an atom is, while the number of electrons is related with its chemical reactions. For example, an atom of Oxygen has 8 protons in the nucleus and 8 electrons, whereas a Hydrogen atom has only 1 proton and 1 electron. Due to their different constitution, atoms of different elements usually don't have the same mass. The mass number corresponds to the sum of the number of protons and the number of neutrons. Figure 2.2 illustrates the representation used to indicate the atomic number and the mass number of an atom.

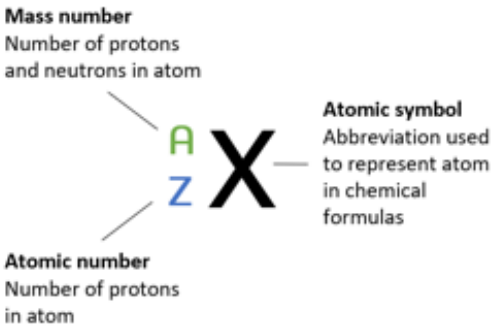


Figure 2.2: Atomic notation[2]

[1]Image based on https://www.deviantart.com/plunderer01/art/U235-NOW-WITH-ELECTRON-CLOUD-113284916 in February 2020

[2]Image based on https://hi-static.z-dn.net/files/d2c/d4c25bdec14f7cd7e69f3523749bad79.jpg in February 2020

This representation allows us to know how many neutrons, protons and electrons constitute the atom. One aspect of the Electron cloud model is that the electrons can only have certain energy levels. The first level can contain a maximum of two electrons while the second level may have eight electrons at most. Table 2.1 shows the electronic configuration of some elements.

Table 2.1: Electron configuration based on [20]

Hydrogen ${}_1H$	**Level 1** - 1 electron	
Carbon ${}_6C$	**Level 1** - 2 electrons	**Level 2** - 4 electrons
Oxygen ${}_8O$	**Level 1** - 2 electrons	**Level 2** - 6 electrons

The electrons from the last energy level are named *valence electrons*. They are, on average, far from the nucleus, which is responsible for the atom size, as well as the interaction with other atoms, and the chemical behaviour of the elements.

Although the Electron Cloud Model is currently the most accepted model, the Bohr model is still used for learning purposes, as it gives a better visualization of the energy levels, as shown in Figure 2.3.

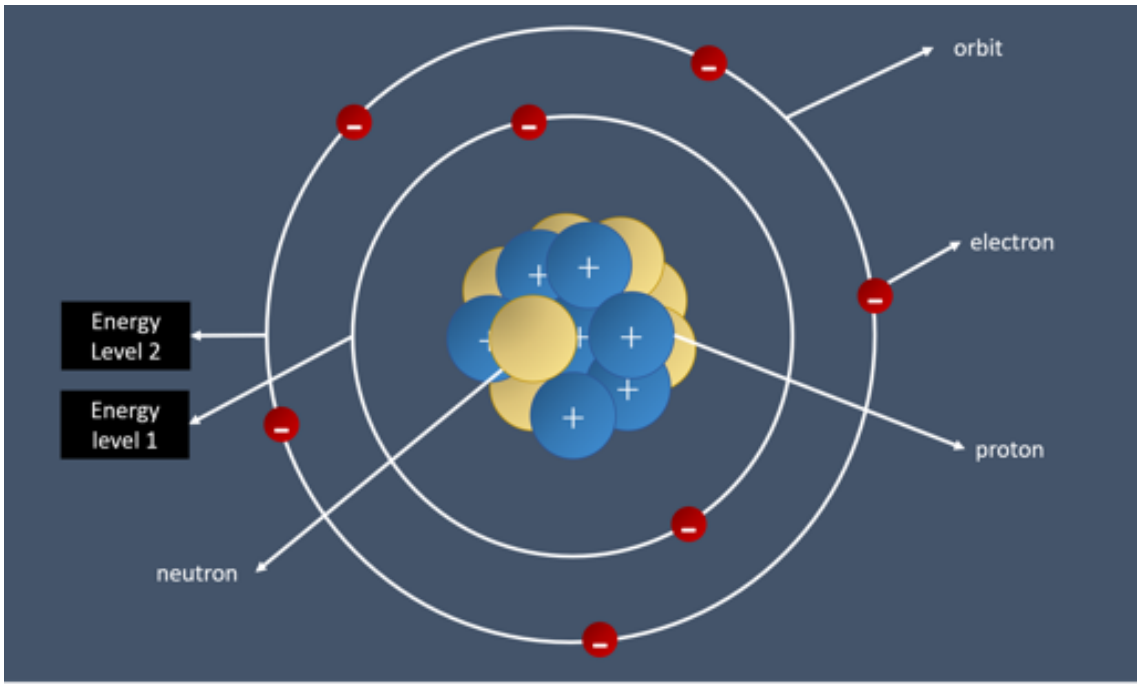


Figure 2.3: Bohr model of the atom[3]

2.1.2 Periodic Table of Elements

Dmitri Mendeleev decided to order the chemical elements in a table, since he verified that their properties repeated periodically. His table served as a base to the current one, that

[3]Image based on https://www.britannica.com/science/Bohr-model in November 2020

has now all the 118 elements (natural and artificial) discovered to date (see Figure 2.4).

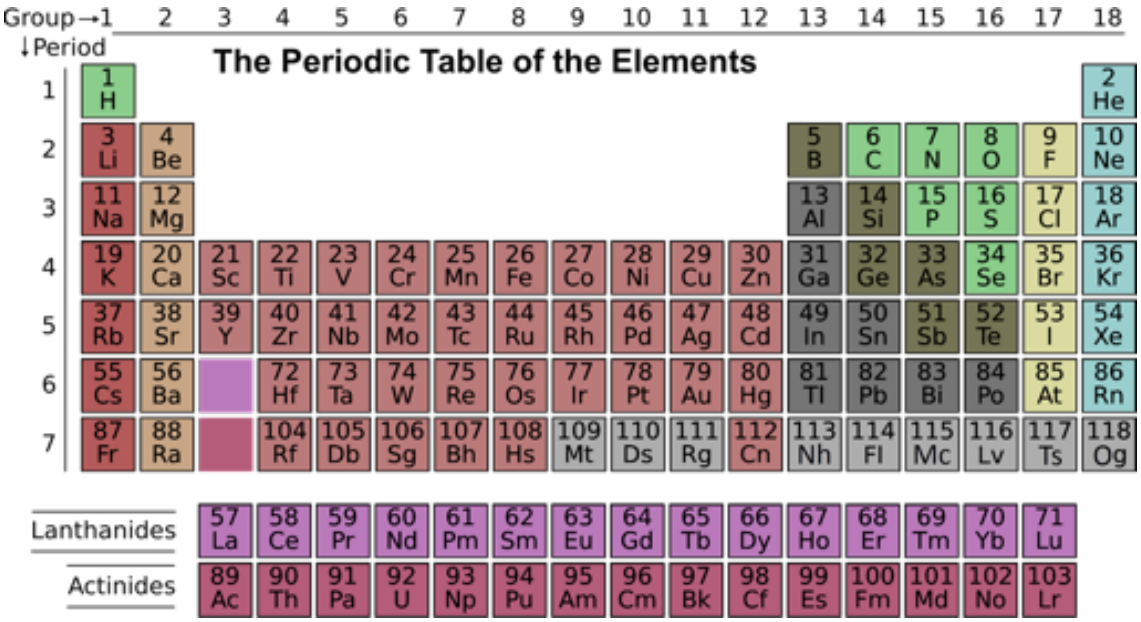


Figure 2.4: Current Periodic Table of Elements[4]

The elements are organized by crescent order of atomic number. The vertical lines are the groups and the horizontal are the periods. The periodic table is organized in terms of periods by the number of energy levels and in terms of groups, depending on the number of valence electrons. The table is also organized by the size of the atoms, increasing along the groups and decreasing along the periods.

There are in total 7 periods and 18 groups. Included in those groups are the alkali metals (group 1), as well as the alkaline-earth metals (group 2), the halogens (group 17) and the nobel gases (group 18).

The chemical elements can also be classified in three categories: metals, semi-metals and non metals.

2.1.3 Molecules and Chemical bonds

The word *molecule* is used to denominate groups of atoms, although there are also monoatomic molecules like the noble gases.

A molecule is represented by a chemical formula, which contains the chemical symbols of the integrant elements and the number of atoms of each element. For example, the water molecule is represented by the H_2O chemical formula, as it contains two atoms of hydrogen and one of oxygen.

When a molecule presents big dimensions, which can have up to thousands of atoms, it is called a macromolecule (e.g. diamond).

[4]Image downloaded from https://pixabay.com/illustrations/ in February 2021

The shape of the molecules depends on the distribution of its atoms in the space. Among the possible geometries we can enumerate the following: linear, angular, pyramidal and tetrahedral.

The atoms can connect to each other through *chemical bonds*. We can consider three types of bonds: covalent bond, ionic bound and metallic bond.

A covalent bond consists on the connection of two atoms, both with tendency to pick up electrons, since this connection is done by sharing them. In order to represent this sharing we can use the Lewis structure.

The number of pairs of electrons shared determines the type of the covalent bond formed between them (see Table 2.2). Each pair of electrons is usually represented by a trace.

Table 2.2: Type of covalent bonds based on [1]

Number of electron pairs shared	Type of covalent bond formed
1	Single
2	Double
3	Triple

Figure 2.5 illustrates the Lewis structure for the water molecule H_2O. Note that, as already mentioned, the Hydrogen has one valence electron and the Oxygen has six valence electrons. In the water molecule, all atoms get their last level filled, with 2 electrons in the case of the Hydrogen, and 8 in the case of Oxygen.

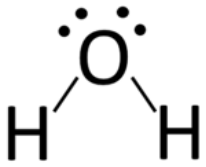


Figure 2.5: Lewis structure for water

However, although the Lewis notation is effective to show the covalent bonds and understand the connection of the atoms, this topic is too advanced for our target group.

2.1.4 Climate change

"Climate change is likely to be the defining issue of the 21st century" [15]. Recently, the fact that climate change poses a serious threat to both human well-being and ecological stability has been increasingly more accepted by the international community [19].

According to the official NASA website, scientists attribute the global warming trend to the human expansion of the *"greenhouse effect"* [47]. The Earth reflects some energy, descendant from the sun light, to space. The remaining energy is absorbed and re-radiated in the form of infrared heat. Most of the heat (about 90 percent) is then absorbed by the

called greenhouse gases (GHGs) and reflected in all directions back toward the surface, warming the Earth.

Among the GHGs, which are made up of molecules, we can enumerate the following: Water vapor (H_2O), Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O) and Chlorofluorocarbons (CFCs).

Although water vapor is the most abundant greenhouse gas, it acts as a feedback to the climate, unlike the others that are released through natural processes and human activities. We opted by not including water vapor as one of the main GHGs in our game since it could give the wrong idea that water is "bad" as it contributes to climate change.

"Concentrations of greenhouse gases are rising faster than at any previous era in the Earth's history", and the evidences no longer pass unnoticed [15]. Phenomenons like global temperature rise, ocean's warming, shrinking of ice sheets, glacial retreat, decreased snow cover, see level rise, declining artic sea ice, rainfall events and ocean acidification are examples of those evidences [46].

Reduction of global food and water supplies, more frequent extreme weather events, and mass extinctions are included amongst the future impacts caused by climate change [53]. Heat stress and vector-borne diseases are expected to cause serious impacts on human health already in the next few decades [8, 15].

Hence, measures need to be taken in order to prevent the progress of the problem. A recent eurostat report [18] shows that the contribution to GHG emissions relies 19% in the households, right after the energy and industry sector (with 27% and 26%, respectively), which makes us conclude that the role of each citizen is significant.

However, people usually underestimate their power to influence climate change, mainly because they fail to understand the correlation between their individual behaviour and its global impact [19]. Then, awareness, engagement and behaviour change need to be promoted.

Regarding behaviour change, Robinson [61] developed the 5 Doors theory, which consists of 5 conditions that must be present in a cycle of behavioural change, as presented in Figure 2.6.

There are some available resources that provide information about options for responding to climate change. The EPA (United States **E**nvironmental **P**rotection **A**gency), for example, presents an extensive list [17] of individual actions that impact the environment. Those actions are grouped by different fields including living sustainably, being green on the road, throw away less, choosing greener products, greening industrial and business processes, and cleaner energy choices. Also the David Suzuki Foundation presents important information regarding climate change including an interesting top 10 list of small practices [22].

Figure 2.6: 5 Doors theory of behaviour change [61]

2.2 Augmented reality

Recent years have seen significant advances in virtual environments, and we can enumerate two well-known ones - virtual reality (VR) and augmented reality (AR). While VR "completely immerses the user inside a synthetic environment" [3], not allowing to see the real world, AR does not replace the real world, and instead complements it, allowing the interaction with 3D virtual objects and tangible objects in real time.

Milgram and Kishino [45] presented the concept of *"Virtuality Continuum"*, illustrated in Figure 2.7, where AR is located between the real world and the Virtual Reality environments.

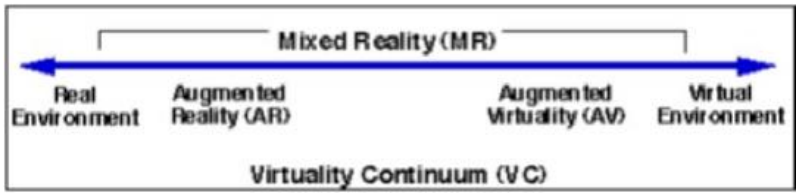


Figure 2.7: Virtuality Continuum diagram [45]

Azuma [3] defines AR as any system that has the following three characteristics:

1. Combines real and virtual
2. Is interactive in real time
3. Is registered in three dimensions

Although AR is not that much of a recent approach, it suffered a major boost recently. Thus, there are some AR apps currently available and used in our daily life like screens in vehicles showing its rear (through cameras) with graphics to help the driver reverse.

Besides these, AR has a lot more applications, like assistance in surgery, tourism, architecture, entertainment [3, 65]. A considerable number of AR mobile apps have also been developed recently as presented in more detail in the next section.

2.2.1 Mobile augmented reality

Augmented reality has a large number of display possibilities, that can be grouped depending on their location and the type of image produced (i.e., planar or curved), as illustrated in Figure 2.8.

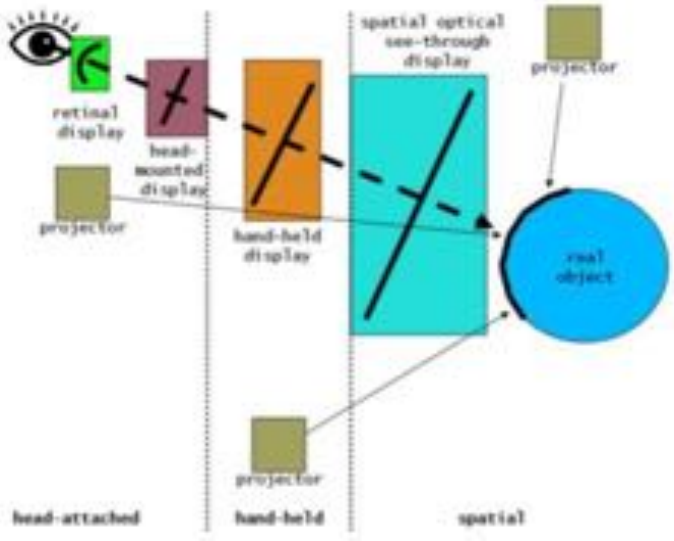


Figure 2.8: Augmented reality displays [5]

In the early days, AR based applications were too expensive and required spending time setting up the system, often using several devices, so it became difficult for everyone to have access to this kind of technology. For example, dedicated devices such as HMDs (Head-Mounted Displays), that were just a few years ago considered the dominant display technology within the AR field, present several disadvantages [5], most of them related to visualization issues, as well as discomfort of these intrusive devices.

However, nowadays, thanks to the growth of cellphone's market, it is easier and cheaper to use AR in our everyday life with the help of a smartphone.

Today's latest smartphones have a sophisticated system, with improved features such as the access to Internet data services, sensors (like camera, microphone and accelerometer) and location-based services (like the GPS) [33, 63, 65] allowing the creation of more complex applications and consequently introducing new augmented environments that "enhance and transform people's experience of physical reality" [63].

Examples of this are the *Pokémon* GO popular mobile game [51] and popular social media face filters. However, besides these, other applications have been created, particularly regarding the exploration of cultural heritage [56] and emergencies [9].

Studies show that it is estimated that AR by itself will play a major role within the mobile future [63].

2.2.2 Tangible augmented reality

Because of the fact that AR works like a bridge between the real and virtual world, it can be applied to all senses, although so far only the sight, touch and audio have been more explored by researchers. This allows the use of physical objects and there are many different ways to interact with them, which should be properly chosen depending on the goal of the task in order to enrich the user experience.

Tangible user interfaces (TUI) were established by Hiroshi Ishii and Brygg Ulmer, and they "augment the real physical world by coupling digital information to everyday physical objects and environments" [31], connecting the cyberspace with the physical environment. Ishii and Ulmer worked around the following key concepts:

1. *Interactive Surfaces*: "Transformation of each surface within architectural space (e.g., walls, desktops, ceilings, doors, windows) into an active interface between the physical and virtual worlds"

2. *Coupling of Bits and Atoms*: "Seamless coupling of everyday graspable objects (e.g., cards, books, models) with the digital information that pertains to them"

3. *Ambient Media*: "Use of ambient media such as sound, light, airflow, and water movement for background interfaces with cyberspace at the periphery of human perception"

Lin et al., 2016 [38], aimed to create an intuitive aircraft control in a 3D flight gaming using physical objects to represent object movement in a 3D virtual space, since that movement involves 3D rotations an translations, which are hard to control in a conventional desktop interface.

Specifically inside of AR context, everyday objects can also be used to represent virtual objects, providing a more real feel to the user. This kind of system was already studied and implemented, particularly by Hettiarachchi et al. [28], with the creation of the system *Annexing Reality*.

2.2.3 A promising approach in education

AR allows students to interact with the learning subject, unlike traditional approaches that put the learner as a passive element during the learning process [48]. Thus, due to its numerous features, AR is potentially useful for education and in fact, recently it was

made a study about this exact subject, regarding the educational potential of augmented reality [36]. Before getting into specific results, this article presents an extended list of AR applications in different fields that have positive effects on the learning process.

Taking a look at the results, these indicate that the field with most potential to use AR technology is Science Education. Regarding to education levels, the results weren't as dispersed, indicating effectiveness in almost every education level, but more potential was demonstrated for the elementary school and university education.

Included in the materials used in the study, results highlight the use of 3D materials, videos, animations and games to be developed with the help of AR technology.

The participants also presented some suggestions regarding AR applications for the science education such as 3D demonstrations of chemical bonds and molecules, and demonstrations of procedural simulations for chemistry experiments.

Their findings also indicate that AR can be used in education to draw users' attention, increasing motivation and academic achievement, and learning through entertainment.

With regard to chemistry subjects, there were already created multiple games and applications using augmented reality combined with tangible objects [10, 21, 48, 68]. This combination makes all sense when it comes to learning molecules in chemistry, since using objects to represent atoms and chemical bonds is an effective approach and a good way to represent them, as they can't be seen in the real world, for being too small. Using augmented reality also allows the simulation of dangerous chemical reactions, that the children could not try in the real world.

2.3 Case studies

This section describes some examples of already created chemistry applications and games, as well as their results, in case they were studied by researchers and are relevant for our work.

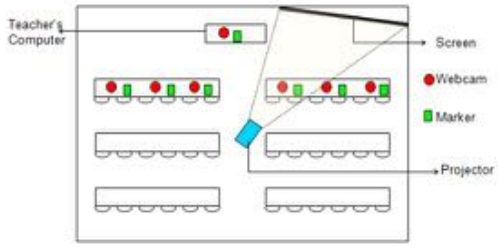
2.3.1 Augmented reality

Though atoms can be illustrated in books as 2D models, these present some ambiguities when representing 3D models. Manuela et al. [48] presented an AR system for teaching Inorganic Chemistry to university students, solving this issue, and it was observed an notable improvement in spatial intuition. In Figure 2.9 we can see the set-up of the system (a) and one of the structures implemented with the associated marker (b).

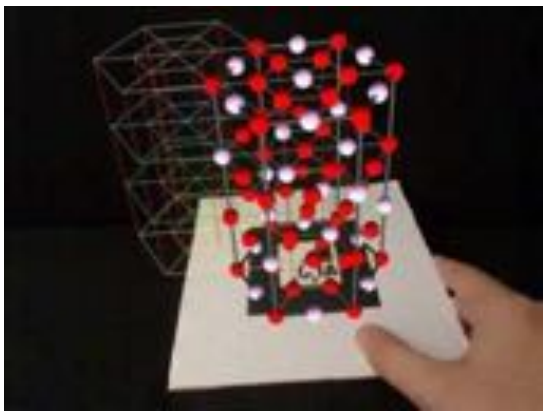
Although there are several programs to visualize the molecules in 3D on a 2D screen, Maier et al. [42] indicates that interactive schemes for rotating or moving the 3D objects in those programs are not intuitive.

Other similar AR applications are *Augmented Chemistry* [21], Yu-Chien Chen application to learn amino acids [10], Taçgin et al. application [68], and Happy atoms[5].

[5]https://happyatoms.com/ accessed in February 2020



(a) Multimedia classroom setup with webcams and markers for the professor and twelve students organized in six groups of two.



(b) the student holds a marker with a corumdum structure

Figure 2.9: Collaborative Augmented Reality for Inorganic Chemistry Education [48]

Augmented chemistry [21] is an interactive educational workbench that shows the constitution of atoms and molecules, using the well-known ball-stick model principle. The system has a set of interactive tools - a booklet, a gripper and a cube, and we can see them represented in Figure 2.10. The booklet shows chemical elements illustrated by a picture and containing a name and, to accomplish a two-handed interaction, the gripper and the cube are supposed to be used by both hands at the same time.

(a) (b) (c)

Figure 2.10: (a) Booklet offering one element per page – here Na – sodium. Each element is represented by a pattern. (b) Gripper with a button (red) and a pattern. (c) Cube with one distinct pattern for each surface. [21]

One hand charges the Gripper with an element from the booklet, and the gripper is positioned next to the platform, that holds a molecule. Rotating the cube with the second hand allows the users to determinate where and how (single- double- or triple-binding) the element shall connect to the molecule. The system set-up is illustrated below in Figure 2.11.

Yu-Chien Chen [10] conducted a study to investigate how students interact with AR and physical objects in learning about amino acids. The AR system used only required a laptop, a webcam to render all virtual objects, and markers. Both AR and physical models showed ball-stick models of five amino acids. The participants of the study

Figure 2.11: System set-up [21]

possessed some basic chemistry knowledge, and the results showed that some of the students preferred to use AR, while others liked to get the feeling of a physical contact.

Figure 2.12: AR system and physical model [10]

Taçgin et al. [68] designed and developed a student-centered AR environment to teach the periodic table and atomic structure of the elements and molecules. The application starts with a periodic table screen, where students can select an element via hand motion to see the corresponding 3D atomic model. Other screens show visual and audial information about an element (one of the options is to see this in VSEPR[6] model), or an element combination.

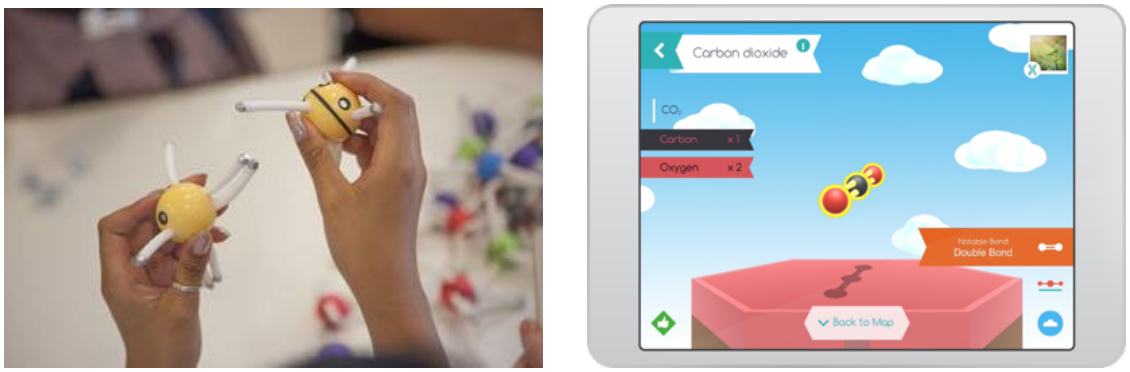
Among recent available AR applications is Happy Atoms[7], which is a tangible, interactive learning tool that combines a digital app with a physical modelling set. This application aims to help students to better learn about atomic modelling and other fundamental lessons in chemistry. The modelling set allows the creation of molecules that connect easily using magnets (see Figure 2.13a), and can be scanned to the digital app, and be further explored (see Figure 2.13b). This application is available both for iOS

[6] valence-shell electron-pair repulsion

[7] https://happyatoms.com/ and https://www.schellgames.com/games/happy-atoms accessed in February 2020

and Android environments and has as main target audience middle school students and families.

All of these chemistry applications have some notable points in common. Besides the use of AR, all applications used tangible objects (usually markers) to represent molecules and atoms, using the ball-stick model principle. Taking into account the positive feedback in terms of learning skills and interaction in the studies, this emphasizes what has been already said regarding to the effective use of AR and tangible objects to represent elements of the periodic table and its molecules.



(a) Plastic atom models

(b) Molecule examination in the digital app

Figure 2.13: Happy atoms application[8]

Another slightly different AR games are the *Periodic Fable*[9] and *The table mystery* [7].

This thesis was originally thought to be a collaboration with Sandra Olim, a PhD student from the Doctoral Program in Digital Media who is developing the project *Periodic Fable*[9] in the Madeira Interactive Technologies Institute, oriented by Prof. Valentina Nisi and Prof. Teresa Romão. However, this collaboration was hard to be maintained due to COVID-19, as we will explain in Chapter 4. Then, this project presents similar features of our own, such as the target group and technologies used.

The *Periodic Fable* mobile application is divided in two parts: an AR Cubes Exploration and an AR World exploration. Firstly, the players can explore 5 distinct physical cubes in the AR Cubes activity. Each cube represents a Periodic Table of Elements' element, and each cube face presents different piece of content (see Figure 2.14):

1. the 3D animated character that represents the element
2. the element location in the periodic table
3. representation of the real world items where that element can be found
4. an activity to combine different elements in order to create different chemical bonds

After exploring the enumerated faces of the cube, the users can create a small puzzle with them (see Figure 2.15), which is going to lead them to the second part of the game.

[8] https://www.schellgames.com/games/happy-atoms accessed in February 2020
[9] https://periodicfable.m-iti.org/ accessed in November 2020

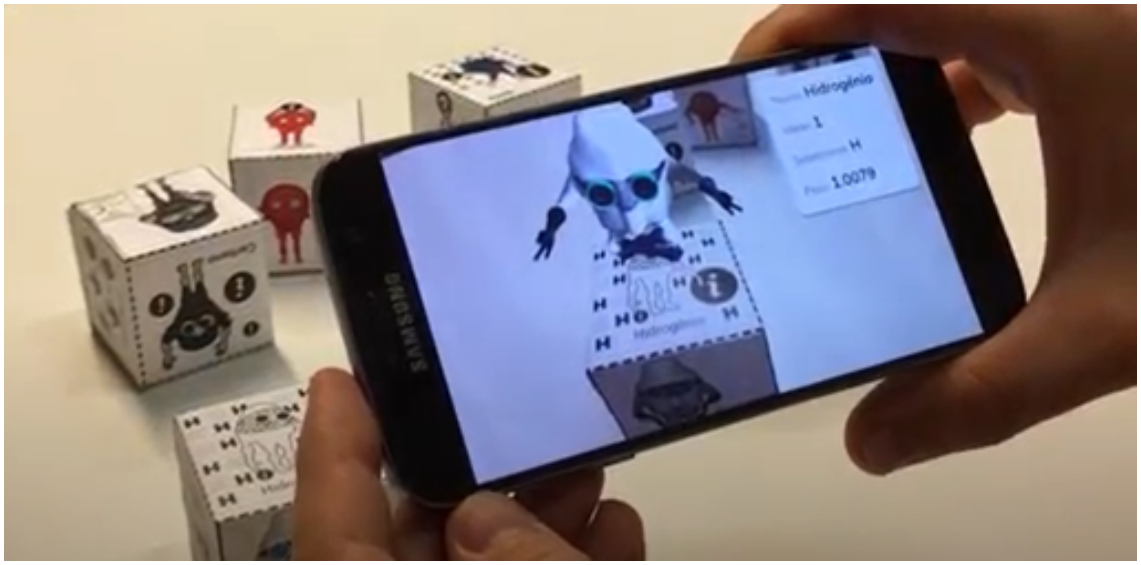


Figure 2.14: Periodic Fable's AR cubes experience[9]

Figure 2.15: User assembling the cubes puzzle[9]

In the second part of the game users can explore an AR world (see Figure 2.16) choosing its favourite character (which represents a chemical element).

This part of the experience focuses on sustainability, introducing new chemical elements that are being affected by human development. Along the way, the player can interact with other elements and he will have to complete several tasks by combining different elements in order to overcome the obstacles and get into the finish line (see Figure 2.17).

After the experience, users are rewarded with a virtual postcard containing a picture with their chosen character.

A recent study conducted by Sandra Olim and Valentina Nisi with 36 young participants demonstrates the potential of the *Periodic Fable* game, and their results show that users were able to learn while engaging in the activity, reinforcing "the positive effects

Figure 2.16: Periodic Fable's AR world main flow - Oxygen (red character) needs to create water to pass to the other side

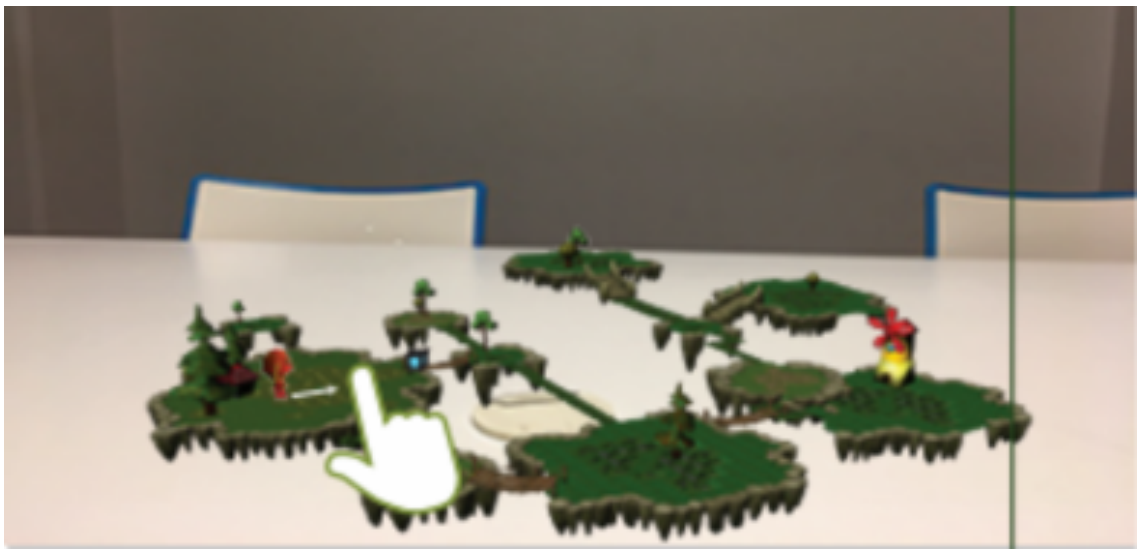


Figure 2.17: Periodic Fable's AR world experience

of gaming techniques and AR technologies in the engagement and motivation of the students" [50].

Lastly, regarding *The table mystery* game, the target audience is students from 11 to 13 years old with some basic knowledge of chemistry. Teams of three players are required to play this game, since each one of them has different roles: one is the technologist, other the researcher, and the last one is the investigator. The goal of the game is to help a man with amnesia to remember who he is and what happened. In order to do that, the players need to answer four Periodic Table related riddles. The technologist accesses the iPad where the man left 3D clues, while the researcher is responsible for using the internet to collect data and the investigator takes notes. In the end, each team solves four quiz questions, revealing a key code for each of them, and the combination of all the key codes unlocks the final secret message which is the solution.

The study aims to examine the efficiency of AR in creating an engaging and motivating educational environment. Results were very positive, showing promising potentials.

2.3.2 Virtual reality

Iris Rodrigues [62] developed an interesting game to teach Organic Chemistry in Virtual Reality, in which the users can interact with the environment by using their hands. The game allows manipulation of virtual molecules, by connecting atoms as well as translate and rotate the molecule.

The goal of the game is to create molecules, by connecting atoms to overcome the challenges presented and progress on the game levels. Those challenges were based on what high school students learn in their freshman year about Organic Chemistry.

Three tests were performed and the results obtained were overall very good, showing that the students enjoyed the game, even the ones that didn't have as much knowledge about Organic Chemistry as the high school students.

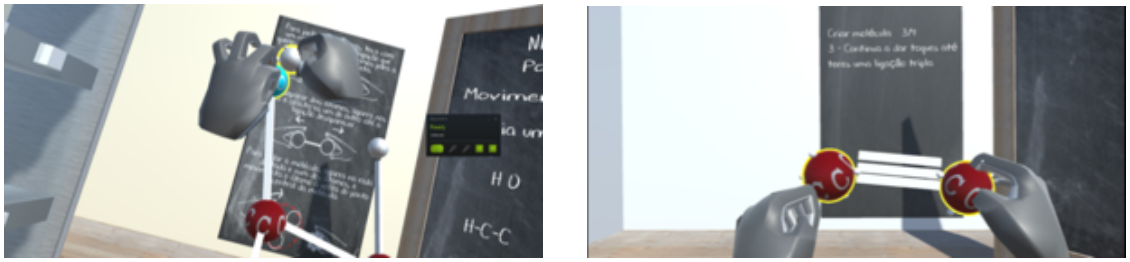


Figure 2.18: Iris's images from the final version of the game [62]

2.4 Learning strategies

"Regarding learning aspects, motivation is the key" [41].

The creation of mobile educational games is growing, and their research usually focuses on the motivational effects of the methods used [30].

Malone and Lepper [43] believe there are seven factors that promote intrinsic motivation: challenge, curiosity, control, fantasy, competition, cooperation and recognition which are often triggered by games [16, 23, 58]. Regarding the different game types, Amory et al. [2] concluded in their study that students are more motivated with games that challenge them to use higher order thinking skills, including game elements such as logic, memory, visualization and problem solving (like adventure or strategy games).

The ARCS model [34] identifies four categories to motivate students in learning, which can be used both for creating motivational strategies, as well as measuring the level of motivation on an educational material:

1. Attention - stimulating and capturing the interest of learners

2. Relevance - the students must understand the importance of the educational proposal

3. Confidence - providing successful experiences arising from learners own skills and effort

4. Satisfaction - reinforcing accomplishment with rewards

Associated with motivation are goals, and, when speaking about children's cognitive and learning process, one must refer the Achievement Goal Theory [11]. Usually when in a class, children don't have an immediate goal, so they would not feel motivated, unless they are truthfully interested in the subject [11]. On the other hand, games present not only well-defined goals but also immediate feedback and a flow, which represents "the feeling of complete and energized focus in an activity, with a high level of enjoyment and fulfilment" [12].

William Swartout and Michael van Lent also mentioned three important levels of goals, that aim to keep players engaged in a game: "short-term (collect the magic keys), lasting, perhaps, seconds; medium-term (open the enchanted safe), lasting minutes; and finally, long-term (save the world), lasting the length of the game." [67].

Merril [44] presents a set of principles about learning, which should be considered when creating an educational game:

1. Problem-centered: "Learning is promoted when learners are engaged in solving real-world problems."

2. Activation: "Learning is promoted when existing knowledge is activated as a foundation for new knowledge."

3. Demonstration: "Learning is promoted when new knowledge is demonstrated to the learner."

4. Application: "Learning is promoted when new knowledge is applied by the learner."

5. Integration: "Learning is promoted when new knowledge is integrated into the learner's world."

During the design and evaluation process, it is also important to understand the different forms of knowledge that learners can develop. Benjamin Bloom [6], along with other investigators, created a classification of six levels of reasoning, ranging from the simplest to the most complex one:

1. Knowledge - recall informations, such as facts, words, places, ...

2. Comprehension - understand the information

3. Application - apply the knowledge in specific situations

4. Analysis - draw connections among ideas

5. Synthesis - combine parts to form a whole
6. Evaluation - judge the knowledge value

Other interesting model is the Kirkpatrick's [35] model for evaluating training programs, presenting four levels:

1. reaction - measures the satisfaction of those who participated
2. learning - "extent to which participants change their attitudes, improve knowledge and/or increase skill"
3. behaviour - identifies how much participants changed their behaviour. In order for that change to occur, the person must: "(i) have a desire to change, (ii) know what to do and how to do it, (ii) work in the right climate, (iv) be rewarded for changing"
4. results - final results that were obtained with the training

Focusing more on the 3rd level, this is useful since we pretend to evaluate behaviour change regarding climate change.

2.4.1 Storytelling

"Storytelling is a simple but powerful method to explain complex matters" [25]. Technologies like films, computer devices, televisions, offer a different way of telling stories when compared with the traditional book approach.

We can tell that storytelling is an effective approach looking at the popularity of the television program *Sesame Street* where children learn through stories. Recent games like *Sims* and *World of Warcraft* also show for their popularity that people like to experience stories created digitally.

Thus, studies show that storytelling helps with the maintenance of motivation [52], which is the main key to keep people interested in a game.

The role of the narrative context in a game for motivating and conceptualizing learning in a 2-D interactive learning environment was analyzed by Waraich [70], who concluded that in order to provide motivation in an educational game, it is necessary that there is a strong story capable of drawing player's attention and learning tasks related with the story.

Regarding climate change subjects, Fernandez et al. [19] empathizes that campaigns need "to have a clear story to tell, with a very concrete action connected to it", in order to create impact. Berger and his colleagues [4] also present Storytelling as one of the six principles of contagiousness, since people tend to share stories, instead of information. Therefore, the focus is to create "innovative useful messages with an emotional undertone and a memorable story line" [19].

Thue et al. [69] presented a set of decisions available during storytelling at three levels, that aim to answer the following questions:

- **Highest level** - How does the story begin? What prompts the protagonist into action?
- **Second highest level** - When, where, and for whom should events occur?
- **Third Highest level** - What are the behaviours of each character?

An interesting example of the use of storytelling is the mobile game *My Café: Recipes and Stories*[10], which age rating is +12 years old. This game is available for both Android and iOS, and it has a classification of 4.5 over more than 3 million votes in the Play store.

The game consists in the creation and improvement of a coffee shop and has different game levels. Through the game, the player can talk with the costumers that tell stories, and eventually they ask the player to help them solve an issue, or make requests in exchange for information of an unfinished story. For example, in one of the stories, the Mona Lisa was stolen, and the player helped solve the mystery by talking to the customers and making the requests to get answers. During the stories, players are often faced with masked learning subjects.

After each mission the player increases the experience in the level and usually gets a reward, in money or diamonds, to buy equipment, improving the restaurant.

My Café creates motivation around users, providing them different stories and information while accomplishing missions.

2.5 User analysis

One of the key steps in a user-centered design is the user analysis.

Since children's cognitive skills are still developing, special care is required when analysing this target group, in order to create effective designs. However, it is important to note that the physical development is not consistent through the age range of children (3 to 12 years old), meaning that only two years apart can indicate different abilities [39, 55].

Of course, this dissertation's research will focus more on the age range of interest, which corresponds to the older children group (above 9 years old).

Jean Piaget, a psychologist that placed great importance on children's education, created the *"Theory of Cognitive Development"* [55], presenting four different stages of children's development, depending on their age. According to his theory, children from 7 to 11 years old are placed in the concrete operational stage, while children from 11 years are in the formal operational stage.

Feifei Liu [39] studies indicate that children from 9 to 12 years-old have their physical ability practically well developed, presenting device preference for laptops and touchscreens, and ability to use both the mouse and the trackpad. Finally, the gestures mastered

[10] https://apps.apple.com/us/app/my-cafe-restaurant-game/id1068204657 accessed in November 2020

at that age are the following: dragging and scrolling with mouse and trackpad, complex coordination between keyboard and mouse.

We can see that older kids have already well developed cognitive capacities, not very far from teenagers. However, it is important to make more flexible designs that can adjust to all profiles of that group, and take into account the speed of development of the skills of each one.

In a more recent study, Feifei Liu [40] pointed five design recommendations for children, presenting several game examples that fit into each point, whether for good or bad reasons. The recommendations are enumerated bellow:

1. Give kids clear and specific instructions by stating the goal of a game (or other online tasks) and how to achieve it.

2. Instructions should be tailored to the kids' level of understanding.

3. Use existing mental models and knowledge about the world to help kids accomplish tasks.

4. Reduce cognitive load by designing self-explanatory interfaces and preventing possible errors.

5. Instructions should be clear and specific, but not too prescriptive.

This research helped to accomplish a more clear understanding of our target users, particularly in terms of their limited physical abilities, which design needs to be fitted, in order to not discourage them.

2.5.1 Children as evaluators

"In the learning sciences, usability testing is essential for creating technology-enhanced learning environments that support specific learning goals" [54].

Several studies have been done using children as evaluators [24, 27, 59]. Janet Read [59], a professor of child computer interaction, argues that users have an important role in evaluation, since they will typically do things that experts might not predict will happen. Janet also claims that after the work in the ChiCI lab with her colleagues, they "firmly believe there is no substitute in usability testing and user studies to having a product tested and experienced by a real child" [59].

Despite this, there are some concerns regarding the process of arranging studies and recruiting children, as well as ethical concerns around the meaning of the children's participation.

Janet Read developed the *Fun Toolkit* [60], a survey instrument used to gather children's opinions about technology. The toolkit is composed by three instruments that can be used with children:

- **The smileyometer** - the most used instrument, is made up of five smileys, codesigned with children aged eight and nine, arranged in a line forming a scale (Figure

2.19). The Smileyometer may be used before the test, in order to measure the expectations of the child, and after, where child can report experienced feelings or experienced fun. In case there are several technologies being evaluated at the same time, as it is the case of our project, Janet claims that the preferred approach is to show a single one at a time for each considered technology.

- **The Fun Sorter** - used to compare many technologies according to different constructs. It works like a table, having $n + 1$ columns (where n is the number of items being compared), and $m + 1$ rows (where m is the number of constructs being used).
- **The Again Again table** - Psychology supports the idea that we are most likely to want to return to an activity that we have liked. Hence, this technique is a simple table where the child has to tick either 'yes', 'maybe' or 'no' for each activity or technology, answering the question "Would you like to do this again?".

Figure 2.19: A Smileyometer awaiting completion [60]

In a more recent study, Hall et. al [26] proposed a Smiley Face Likert (SFL) scale rating method named *Five Degrees of Happiness*. The 5 Degrees of Happiness SFL, illustrated in Figure 2.20 provides positive responses only.

Figure 2.20: The 5 Degrees of Happiness SFL [26]

According to their results, unlike the traditional approach, where children from 9-11 years old rated from 4 to 5, the entire scale was used in the Five Degrees of Happiness. This made them conclude that their created scale provides "an effective method for children to provide judgments in response to scaled quantitative questions".

Lorna et al. [24] discussed the role of children as expert evaluators in the assessment of accessibility and usability. It is important to refer that the average age of this study's users was 10 years old, which fits the age range of this project's target group.

The study describes children as being very energetic, always looking for something stimulating, and presenting a limited attention span, which can be good qualities during evaluation. The evaluation was made through a task list of ten questions, treated as a mini quiz, in order to understand the difficulty of the tasks, and areas with particular navigational difficulties. Their evaluation was proved very helpful, giving useful information such as the font size used and button control navigation.

A similar study was made by Libby et al. [27] to eight- and nine-year-old children. Results suggested that rankings and discussion of rationale were more effective than

ratings and open-ended questions, which made researchers conclude that "children can effectively evaluate the appeal and potential of game concepts with appropriate methodology".

Chapter 3

Chemistry with a hint of magic

This Chapter focus on the explanation of the proposed approach to solve the problems identified in Chapter 1. The concept and mechanics of the solution were formulated taking into account important results of the literature review presented in Chapter 2.

3.1 Domain and technologies

Before formalizing the idea to solve the problem, it is important to set the chemistry domain in which the project should focus.

Our research shows that the educational chemistry concepts that present more learning challenges require abstract thinking [14, 57]. One example of this is the Periodic Table, which as proven to be a fundamental topic, since it introduces basic concepts that are the foundation to understand more advanced ones [57]. Figure 3.1 shows the concepts related with the Periodic Table and the relationships between them.

After the domain is assigned, it is important that appropriate technologies are chosen to provide both efficient learning and engaging experiences for the users. According to our research, the following elements present potential regarding these goals:

1. **games** - promotes motivation regarding educational subjects [16, 23, 58]

2. **augmented reality** - results suggest AR is a powerful tool in the learning process and specifically in chemistry since it allows the representation of 3D models, helping to understand abstract concepts like atoms and molecules [10, 21, 36, 48, 68]

3. **physical objects** - combined with AR technologies, allows users to interact with the augmented world, and helps them to control 3D models in an easier way, improving their visual and spatial skills [37, 38, 42, 48, 57]

Figure 3.1: Chemistry related abstract concepts and relationships between them

4. **storytelling** - helps to explain complex matters, connecting different concepts [25], helps with the maintenance of motivation [52, 70], and creates impact regarding climate change subjects [19]

Finally, the mobile phone was the chosen display due to its mobility, affordability and simplicity [33]. They are also the preferred device of our target group [39], who can handle them easily, so it takes no time for adaptation.

In short, the proposed approach is based on a smartphone game, that allows children from ages 9 to 12 to explore basic chemistry subjects as well as inform and encourage them to act in an environmental friendly matter. This game, named *Magic Elements* (the game logo is shown in Figure 3.2), utilizes storytelling, augmented reality and physical objects, which not only provide an engaging experience, but also contribute to a more efficient learning.

3.2 Game theme

One of the first things that was delineated in the game was its theme. Soon we realized that *"magic"* was the most suitable one for the purpose we were trying to achieve.

First, the association of science (and more specifically chemistry) with magic comes from many years, related to the alchemy practices [29].

Magic is also part of fantasy, which is a preference theme of the younger generations [16, 23, 58].

However, the major reason that makes magic an important theme is that the hypothetical use of magic by the player in the game gives him more freedom to manipulate and

Figure 3.2: Magic Elements game logotype

interact with abstract models like atoms and molecules, while it clarifies the idea that that interaction and manipulation is not possible in the real world.

After the magic theme was set, we could think about all kinds of actions the player could make by using magic. Then, we were ready to formulate the concept and structure of the game.

3.3 Game description

3.3.1 Game plot

The fictitious premise of Magic Elements happens in a virtual Earth's parallel world, named Lemuria. Lemuria is a planet similar to Earth in many aspects, except that it was created with an environment that allows the use of magic. Just like on Earth, Lemuria is suffering from climate change. The only Lemuria's wizard is Auberon, which is an old man and whose magic powers have become weaker, so he cannot face the climate change problematic by himself. Lemuria's last chance to fight the causes of climate change is to find a human (the player of the game) to become the next wizard.

The player will have to go through different game levels, increasing the difficulty in each of them, to improve his wizard skills. In each game level, the player will be in a different place of Lemuria and he needs to do a set of actions (that will be explained with more detail in section 3.3.5) related with a chemistry topic and/or responding to climate change to find an exit and leave the current place in a limited amount of time, just like an Escape room[1] game, which features fit into the types of games that most motivate students [2]. Figure 3.3 illustrates the structure of our game levels, explained with more detail in the next sections.

[1] https://theescapegame.com/blog/what-is-an-escape-room/ accessed in November 2020

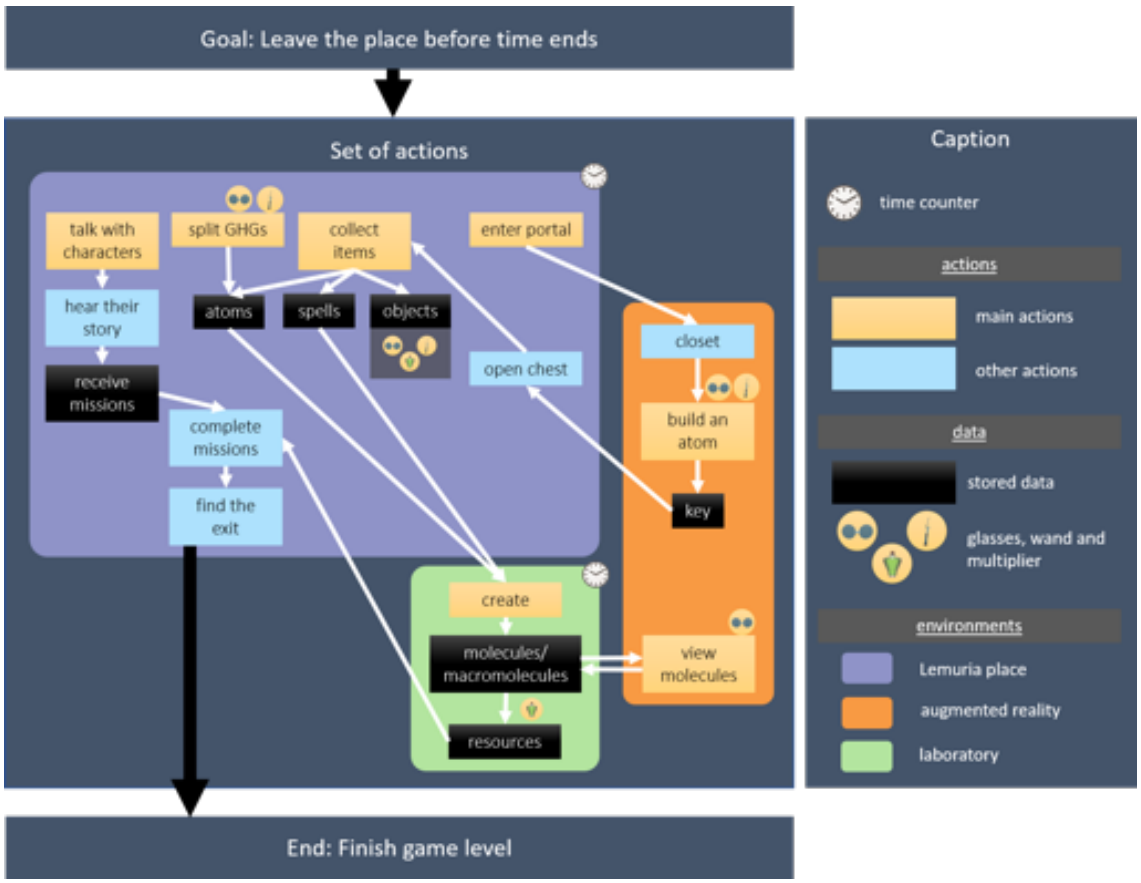


Figure 3.3: Structure of a Magic Elements' game level

3.3.2 Interface

The interface of our game was designed in a way that intents to clearly transmit the necessary information to the player.

A game level takes place in three main environments (that will be described in more detail in section 3.3.7), each one with a different interface that is adapted to the actions that can be done in that environment.

A substantial part of the game is spent in a place of Lemuria, which is the main environment of each game level and consequently contains the most important visuals.

To execute the actions, the player uses three main controls: a movement joystick, a camera joystick and an action button. There is also a set of informations that the user needs to be able to see, such as the current game level, the time left (for the game to end), guidance text and the game items and missions. Since the player can navigate to the laboratory at any time, the interface also contains a button to do it. Finally, a game level can be paused at any time, by accessing the pause button.

Figure 3.4 illustrates all of these elements.

During the first game level, an interactive tutorial is presented to the player so that he can understand the game. While the player executes the actions, guidance text is presented in the information panel accompanied by an animation that specifies which

Figure 3.4: Scheme of the Lemuria place interface

control the player should use (see Figure 3.5).

Figure 3.5: Tutorial - Auberon giving guidance text while arrow animation points to the spell book

3.3.3 Character options

Before the users start playing the game, they will come upon the character screen selection (see Figure 3.6). The chosen character will represent the player throughout the game levels, but the player can switch it at any time in the Main Menu (see Figure 3.7), without affecting his game progress. Currently they can choose between a boy and or girl, however, more characters can be easily added in the future.

Figure 3.6: Choose your character screen

Figure 3.7: The main menu allows the player to switch his character at any time

3.3.4 Game levels

When playing a game for the first time, after the player chooses his character, he is redirected to the main menu, where he can start the game. By making that choice, the player will access the game levels list where he can play the first game level (see Figure 3.8). The other game levels are only available to be played after the previous ones are concluded. For example, to unlock the second game level, the player needs to complete the game level number one first. This happens since the difficulty increases throughout the game levels, and it also aims to motivate the player to complete the game levels to unlock new ones.

Each game level happens in a different place of Lemuria, but all places are connected to each other. For example, the first game level occurs in the enchanted lake, and the goal

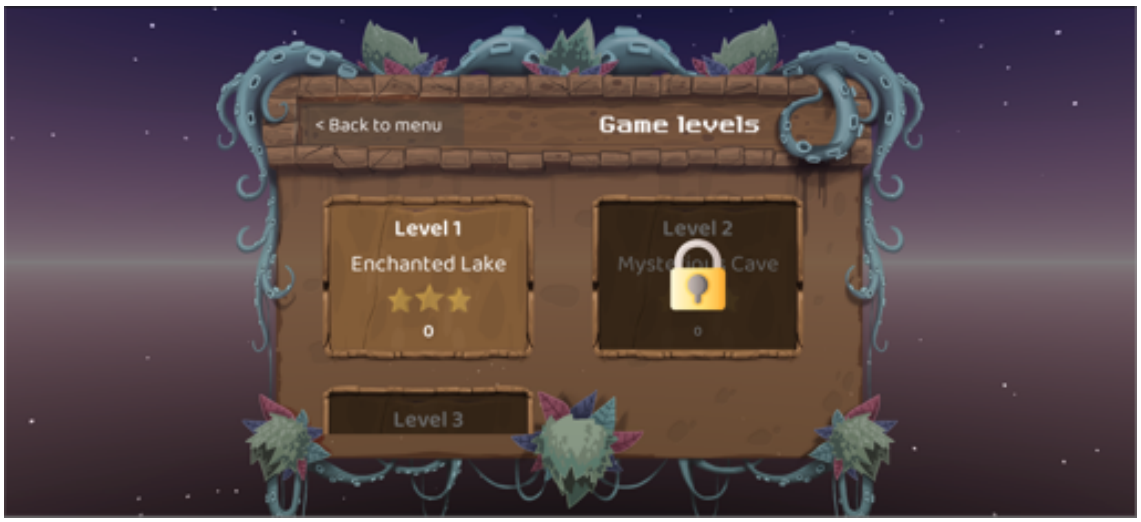


Figure 3.8: Game levels list screen when playing a game for the first time

of the player is to find an exit of that place. The player leaves the first game level using a boat to cross the lake. Then, when he finishes the game level, he can go to second one, where he starts at the other corner of the lake.

After the player leaves the place in a game level, which only happens after he performed all possible actions, he completes the game level and a score number for that game level is calculated, using a simple algorithm, depending on the player's performance which is quantified by the time it took for the player to finish the level. Besides the score number, a game level is marked with one (low score), two (medium score), or three (high score) stars. This technique has as main purpose to encourage the user to repeat the game levels and increase his score. Figure 3.9 shows the game levels list after the player completes the first two game levels, indicating the respective score number and stars obtained in each game level.

The last version of the game contains two fully developed game levels, and a third one that contains a dialogue screen explaining that Lemuria is still suffering from climate change and that more game levels are being developed, encouraging them to repeat the previous game levels. New game levels can be easily added in the future.

3.3.5 Main actions

Just like an Escape room game, in each level of our game the player needs to collect items, create resources using the items, be attentive to clues and solve puzzles/minigames. These actions trigger events like opening a door, show other items or new paths, contributing for the player progress and putting him closer to find the exit to leave the current place in the allotted time.

Specifically in our game, those actions (collect items, create resources, solve puzzles, ...) were thought in a way that they can convey the concepts presented in the domain of our game (described in section 3.1).

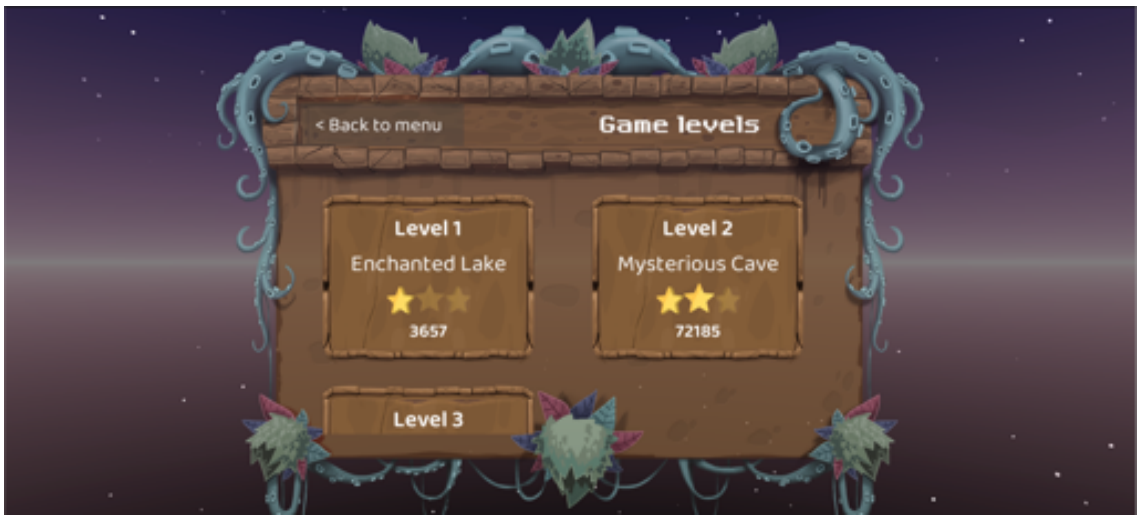


Figure 3.9: Game levels list screen after completing game levels number one and two

3.3.5.1 Collecting items

The player can collect items of three types: objects, spells or atoms.

The first three objects that the player will collect in the first game level are magic glasses, a magic wand, and a magic multiplier. These objects are important since they will allow the player to do the actions that will follow in all game levels:

1. **Magic glasses** - necessary to see molecules and atoms (which cannot be seen in the real world given their small sizes)
2. **Magic wand** - used in all player actions that require the manipulation of molecules and atoms
3. **Magic multiplier** - since one molecule is not enough to represent a resource (for example, 1 gram of water is composed by approximately $3.3455*10^{22}$ water molecules), the magic multiplier turns molecules into resources, by multiplying them.

Figure 3.10 shows the player collecting the magic glasses in the final version of the game.

Regarding spells and atoms, these can also be collected by the player and they will be necessary to create molecules and resources, as we will explain in section 3.3.5.3.

After the player collects the items, these will be stored and will be always available to be used when needed.

(a) Player before collecting the magic glasses

(b) Magic glasses information after its collection

(c) Player with the glasses on

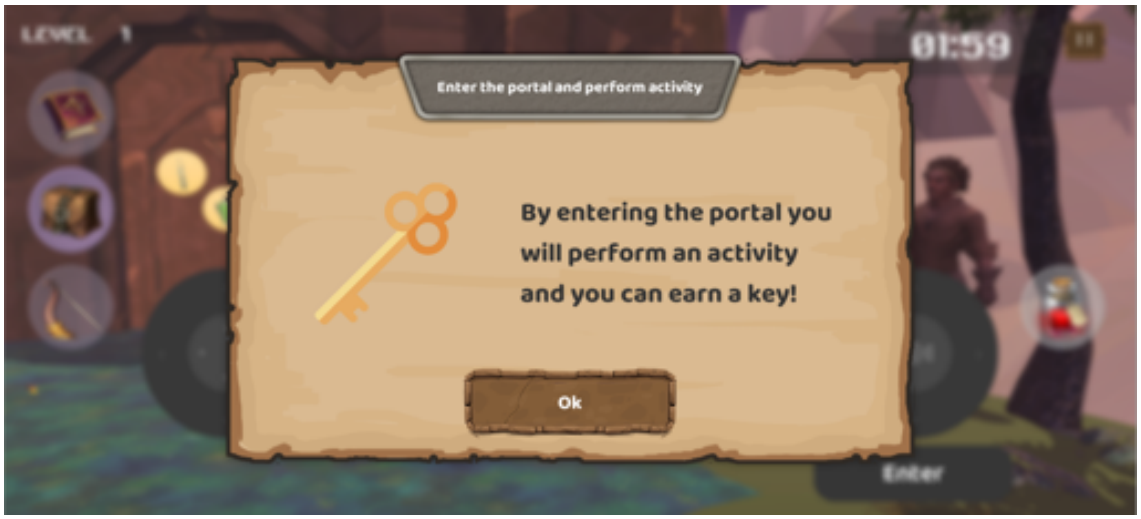
Figure 3.10: Player collecting the magic glasses

3.3.5.2 Augmented reality activities

Not all items are available for the user to see and just collect them. Some items are hidden in closed chests which can only be opened using keys.

To gain those keys, the player can enter a portal (see Figure 3.11) that leads to an augmented reality activity (a minigame), where the player is going to build an atom of a certain element using physical cards.

(a) Player before entering the portal



(b) Portal information

Figure 3.11: Enter portal

Before building an atom the player first chooses some wizard accessories and face filters that he can use (see Figure 3.12). Besides the glasses and the wand, the other filters are optional to be used in the activity. This extra action aims to provide more engagement to the player, and reminds him that the magic glasses and wand are necessary to see the atom and manipulate it, respectively, in the AR activity.

After choosing the accessories to bring to the AR activity, the player will follow some

Figure 3.12: Player choosing accessories in the augmented reality closet

instructions to create an atom of a certain element (the element depends on the game level). The activity basically consists on creating the model of an atom, and adding the respective particles to it (protons, electrons and neutrons).

By scanning the card (all cards are illustrated in Appendix A) that corresponds to the element of the desired atom, a 3D electron cloud model is showed (see Figure 3.14a). Since the cloud is formed by the enormous velocity of the electrons, it might be hard for the player to have a perception of them. Then, by using the magic wand the player can stop the electrons, and see them represented by the Bohr atomic model, where the electrons describe well-defined orbits.

The element card follows an atomic notation, showing the atomic symbol of the element in the center, the mass number in the upper right corner and the atomic number in the lower right corner, indicating the number of particles of that element, as shown in Figure 3.13.

Thereafter, the player can add the particles to the model by scanning its corresponding cards and consequently clicking a button labelled with "Add (name of the particle)" (as shown in figure 3.14b), that adds one particle at a time to the model. For example, to add the protons to the oxygen atom model, the player scans the proton card, and adds the protons one by one by clicking in the "Add proton" button, until it reaches the blue number of the card (in this case, 8 protons).

When the atom is fully built (see Figure 3.14c), the player receives a key that can be used afterwards to open the chest in the Lemuria place (see Figure 3.15).

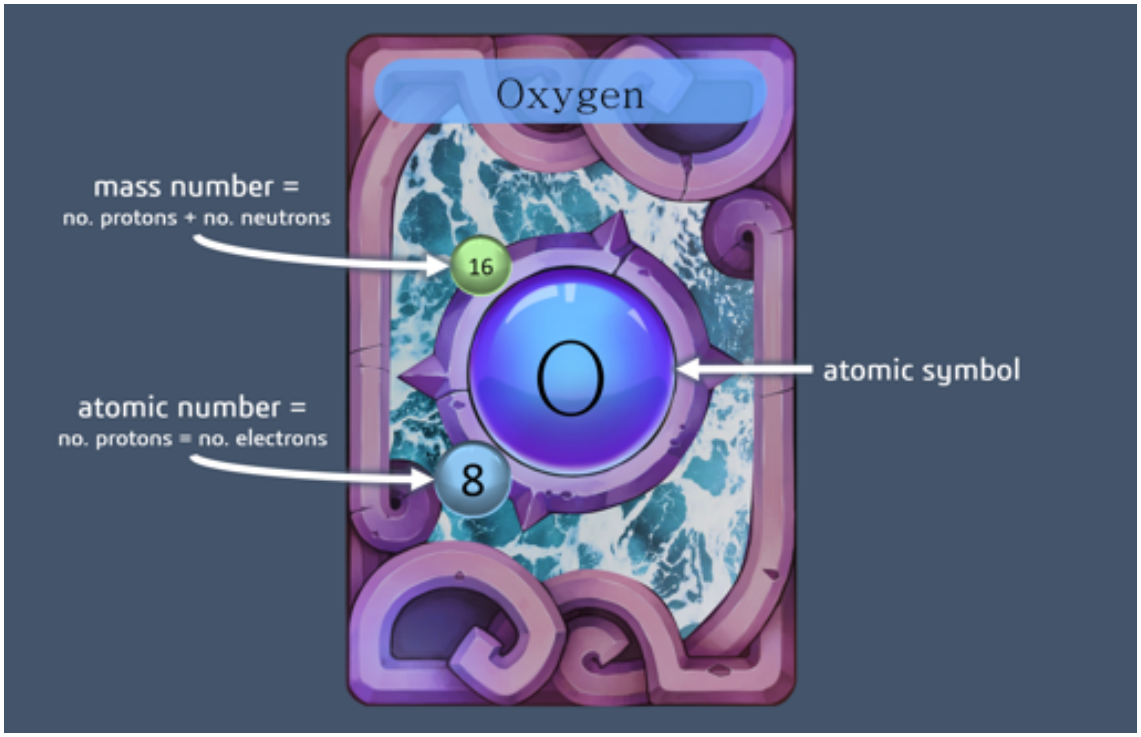


Figure 3.13: Oxygen card

(a) AR electron cloud model

(b) Adding protons to the oxygen Bohr model

(c) Final built atom with information

Figure 3.14: Augmented reality activity to build an atom

(a) Earned key

(b) Player before opening the chest

(c) Player after opening the chest

Figure 3.15: Opening the chest with the earned key

3.3.5.3 Creating resources

As stated before, the main solution to soften climate change is to reduce the emissions of the GHGs. Then, we though that it will be an interesting action for the player to split GHGs molecules (using the magic wand) to get the corresponding atoms, and then use those atoms later to form resources (environmentally friendly molecules or macromolecules). For example, if the player gets close to a molecule of CO_2 (which is a GHG), and decides to split the molecule, it results in 2 atoms of Oxygen (O) and one of Carbon (C) (see Figure 3.16).

(a) Player before splitting a molecule of CO_2

(b) Player after splitting a molecule of CO_2, with the resulting atoms on the floor

Figure 3.16: Player splitting a CO_2 molecule

Those atoms are collected and stored (the storage process is explained in section 3.3.6) and can then be used to form other molecules or new macromolecules. The player will know how to create a certain resource by collecting and viewing its spell (see Figure 3.17). Since all the atoms that the player collected after splitting the GHG molecule were stored,

the user can combine them in the lab according to the spell to form the needed molecules.

For example, if the player has collected 2 atoms of Oxygen(O) and one of Carbon(C) from a (CO_2) molecule he split, he can form dioxygen (O_2). The remaining atom of Carbon remains stored and can be used later to form other resource.

Figure 3.17: Dioxygen spell - two atoms of O (oxygen) and the multiplier

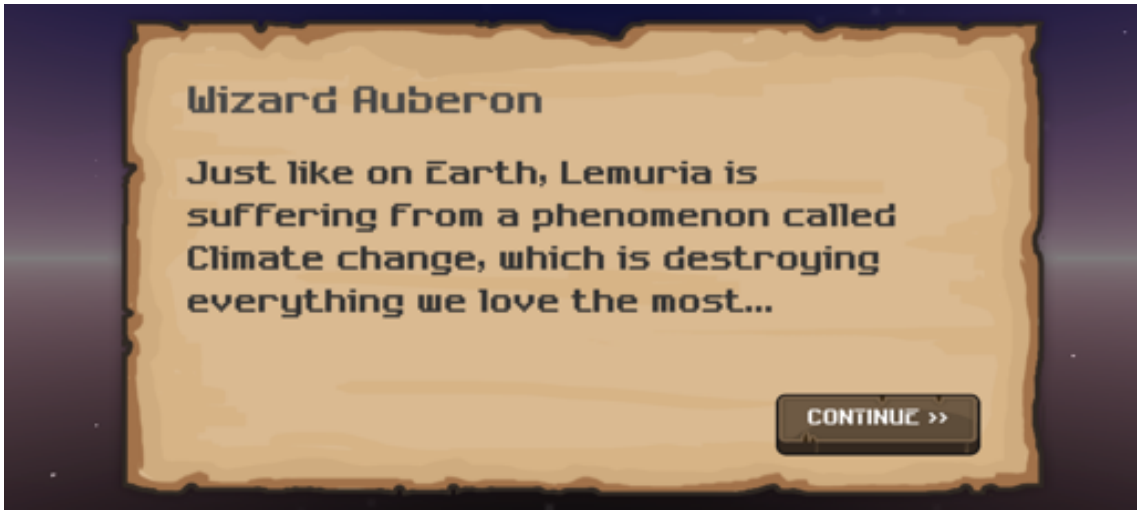
The spells present the chemical formula (in case the resource to be created is composed by molecules) which will always be added to the multiplier to create the actual resource. In case the resource is a macromolecule, that don't exactly have a chemical formula, the player will have to add a certain number of the constituent element of the macromolecule (represented in the spell) and use a collected magic object that sets the structure of the macromolecule. For example, to create a diamond the player needs to collect 5 atoms of the element carbon and the magic diamond structure in order to create the resource.

Another interesting feature that happens after splitting a molecule is the molecule timer. This timer (illustrated in Figure 3.16b to the left of the bubble that previously contained a CO_2 molecule) prevents the player from splitting infinite molecules and represents its "production" time. For example, since CO_2 emissions are bigger than CH_4 ones, the CO_2 timer will be smaller, meaning that it is "produced" faster. The timer starts counting from the moment the player splits the molecule, and until that time ends the player cannot split the molecule, since it is being "produced". Note that this timer only lasts seconds, also to reinforce the idea that the GHGs are produced at a great speed.

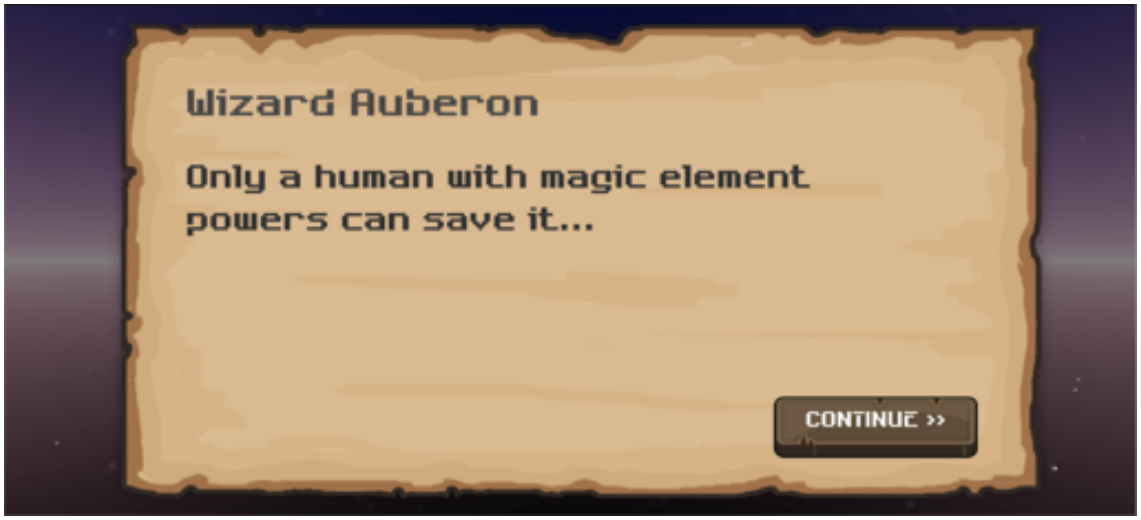
3.3.5.4 Talking with characters

There is one more available action for the player in each level: talk with other characters.

The wizard Auberon is the first character to interact with the player even before he starts a game level. Before the actual game starts, the player receives a letter from Auberon explaining the climate change problematic and why they need a human to become the next wizard (see Figure 3.18).



(a) Auberon explanation screen one



(b) Auberon explanation screen two

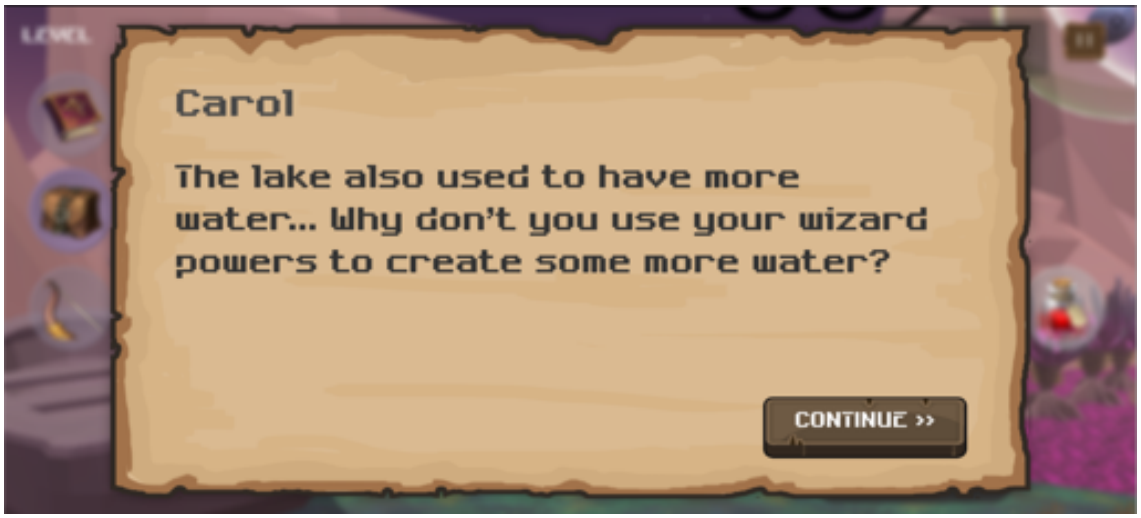
Figure 3.18: Auberon explaining the climate change problematic in Lemuria

Auberon is also present in the game levels and guides the player throughout the game, giving him clues and tips (see Figure 3.10a).

In each game level the player can interact and talk to two other characters. One of those characters is Carol, the florist of Lemuria. Carol likes to share her personal stories that aim to sensitize children to the climate change problematic using evidences (climate change impacts with animals, plants, climate phenomena, ...). Besides telling stories, Carol gives some missions for the player to accomplish, related with the stories she tells but not necessarily related with climate change evidences (see Figure 3.19).

The other character is called Vinicius, who is the teacher of Lemuria, and he has a strong attitude regarding the climate change problematic by doing small individual practices. Just like Carol, he shares his experiences through the tale of a story and aims to teach some of his tips to the player (see Figure 3.20).

(a) Player before talking with Carol

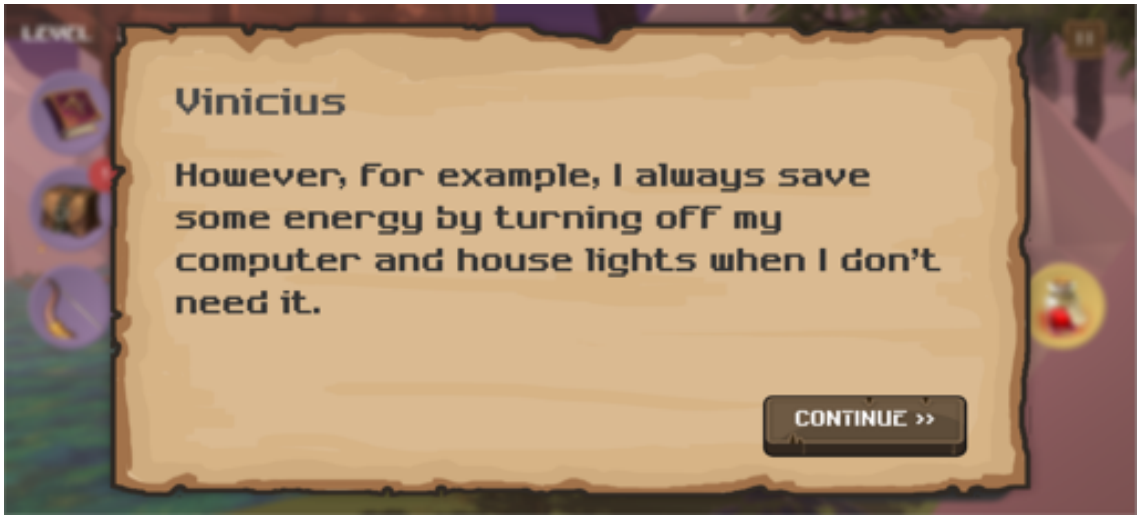


(b) Carol dialogue attributing a new mission

(c) Fill lake mission

Figure 3.19: Player talking with Carol

(a) Player before talking with Vinicius



(b) Vinicius giving player a tip

Figure 3.20: Player talking with Vinicius

3.3.6 Storage system

As already mentioned, there are some data (such as game items and missions) that needs to be stored throughout each game level such as the collected objects, atoms, spells, created resources and missions.

We decided to divide that information in three groups: the spell book, the inventory, and the missions list. The spell book, as the name implies, contains all the spells the user collected (see Figure 3.21).

Figure 3.22 illustrates the inventory, which is divided in four sections: objects, atoms, molecules and macromolecules. Each section presents the items that belong to that section, and the player can access its quantity and description if the item was already discovered/collected.

Lastly, the missions list presents the set of missions that the user needs to accomplish

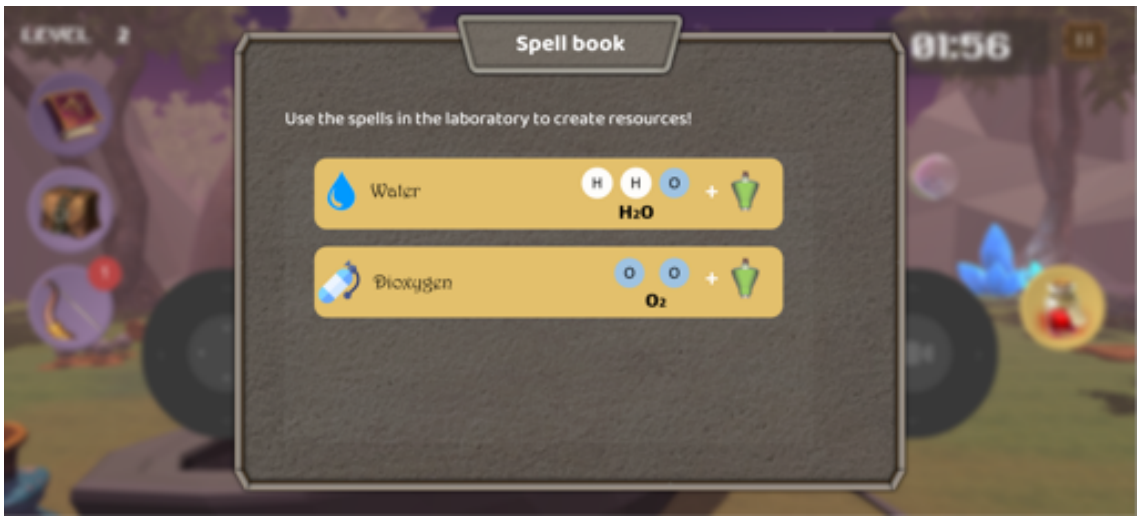


Figure 3.21: The spell book

Figure 3.22: Inventory

(see Figure 3.23).

As already mentioned in 3.3.2, the graphic interface contains three data access buttons, that correspond to each storage group, so that the player can access the items and missions at any time. At the top right corner of each button, there is a number inside a red circle (see Figure 3.24) whenever a new spell is collected (in the case of the spell book), a new object, atom or resource (in the case of inventory), and a non completed mission (in the case of the missions list). Particularly in the case of inventory, each item also shows a red circle that specifies if the item is new (collected or created for the first time) or if its quantity increased since the last time the player visited the inventory, as shown in Figure 3.25.

Figure 3.23: Missions list

Figure 3.24: General Inventory notifications

Figure 3.25: Inventory atoms notifications

3.3.7 Game level environments

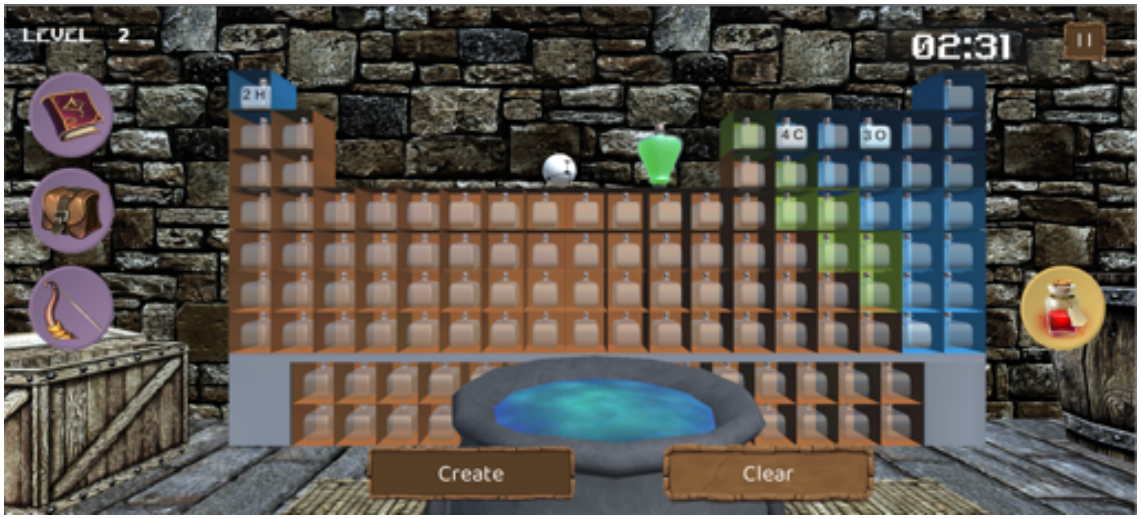
Each game level has three environments: a Lemuria place, the laboratory and the augmented reality room.

The player always starts the game level in a Lemuria place, where he can do actions like collect items, split GHGs, talk with characters and enter portals.

In case the player enters a portal, this leads to an AR activity, as explained before in section 3.3.5.2. After the AR activity is completed, the player receives a key and goes back to the Lemuria place to use it to open a chest.

When a player wants to create a resource, he needs to do it in the laboratory, which contains a shelf with a Periodic Table of Elements shape. In this shelf, the player can view the quantity of each atom that he collected (also present in the inventory), and combine them to form molecules and create resources (see Figure 3.26). While the player is creating a resource, before he uses the multiplier to turn the molecule to an actual resource, he can view the molecule in 3D, by accessing to an AR molecule viewer (see Figure 3.27).

When moving from one environment to another, a loading screen is shown. In order to take advantage of this screen, we decided that it should show, in addition to a progress bar, a phrase related with the game's chemistry domain, as shown in Figure 3.28. Then, we choose a set of phrases related to the chemistry concepts covered in the game and every time the loading screen is shown it presents a different one.



(a) Periodic Table of Elements shelf indicating the quantity of each atom before creating dioxygen

(b) After putting two atoms of oxygen in the cauldron, the player can see a 3D dioxygen molecule and the atoms quantity in the shelf is updated

(c) After adding the multiplier, the player is ready to create the resource

Figure 3.26: Creating an O_2 molecule

Figure 3.27: Augmented reality molecule viewer

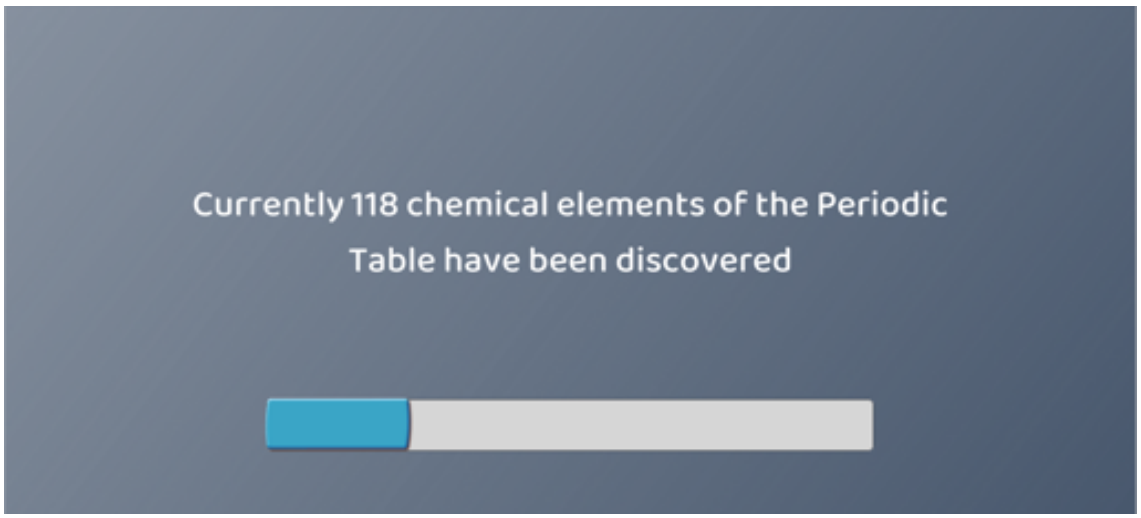


Figure 3.28: Loading screen

3.3.8 Game level checkpoints

Since all game levels have a limited time to be completed, it may happen that the player can't win a game level at first. In such case, a game over screen will be showed (see Figure 3.29), and the player can retry the game level without loosing all of his progress.

It can be demotivating for the player to repeat an entire game level specially when there was a big progress and he was really close to the end.

Then, all game levels have several checkpoints that save the progress of the player. The game level number 2 saves a checkpoint for each action of the player, so he doesn't lose any progress at all if he wants to retry the game level. The game level number 1 also has several checkpoints, however, since it presents an interactive tutorial where there is a flow and some actions are depending on others, the number of checkpoints is a bit smaller comparing to the second game level.

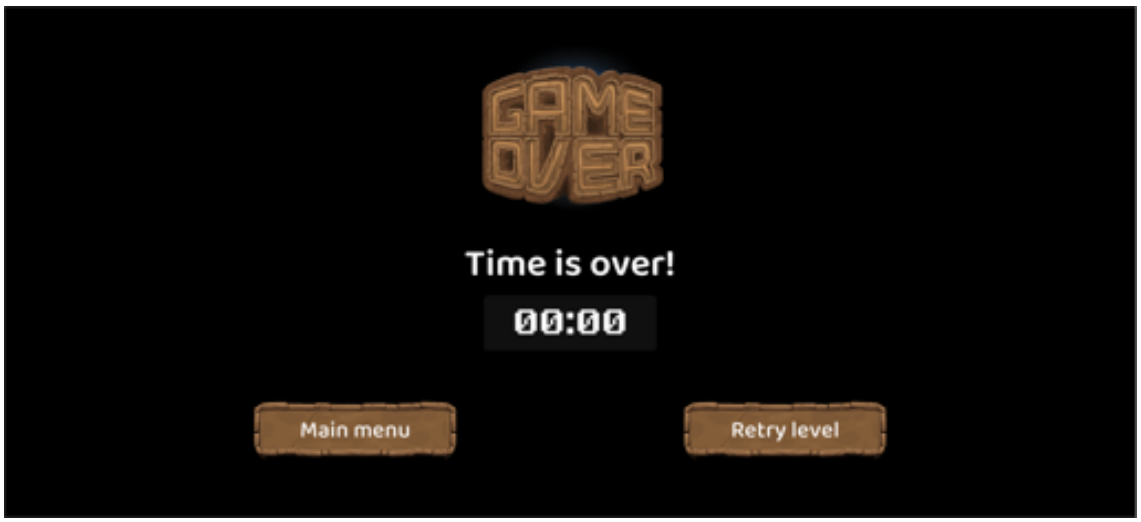


Figure 3.29: Game over screen

By retrying the game level, the player will return to the last saved checkpoint, and he will have only 1/3 of the total game level time to finish the game level. Since the score depends on the time, it can be unfair for those who managed to win at first to have the same score as the others, so the 1/3 of the total time for non first times prevents this. In the current version of the game, the player can retry the game level as many times as he wants to.

It may also happen that the player did not have a lot of progress in the game level, so he might just want to repeat the entire game level. If that's the case, the player can return to the main menu and restart the game level (see Figure 3.30).

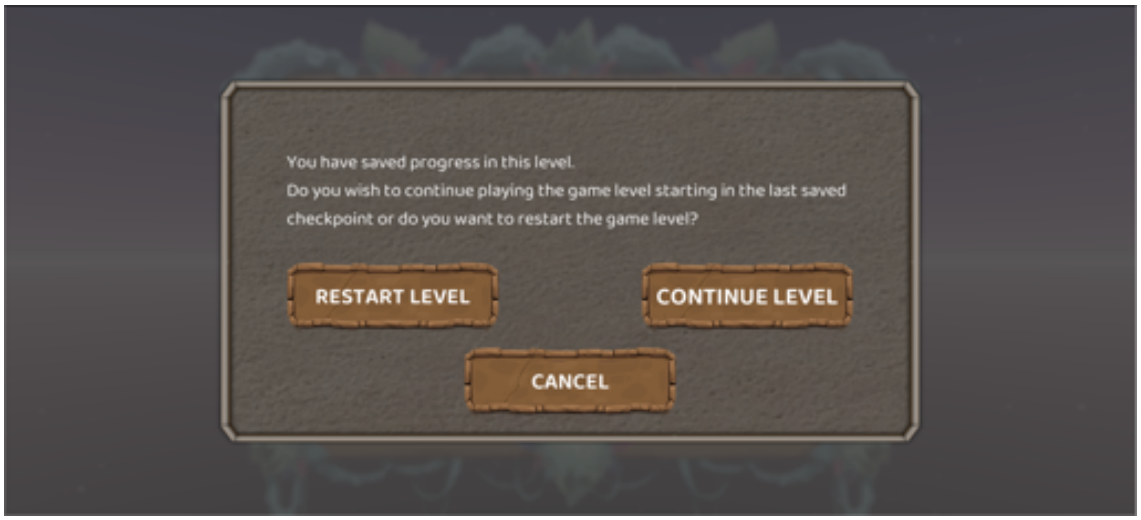


Figure 3.30: Game level options screen

3.3.9 Game levels content

In the first game level the player will collect 4 items: the magic glasses, the magic wand, the multiplier, and the water spell.

The first item to be collected are the magic glasses, that will allow the player to see the GHGs. Then, the player can collect the magic wand to split the only visible GHG (which is a CH_4). Note that the player will be accompanied by the tutorial to perform these first steps and understand the gameplay.

After splitting the CH_4 molecule, a portal will show up. At this point of the game level the player can see the portal, a door that requires the collection of 3 objects (the glasses, the wand and the multiplier) to be opened, and a chest. The multiplier is hidden in the chest, so the only player option at this stage is to enter the portal to earn a key and open the chest. After opening the chest and collecting the multiplier, the door opens leading to a place containing a dry lake next to Carol, a boat, a water spell and other GHG molecule (CO_2).

To enter the boat and leave the Lemuria place, the player will have to create water, using the corresponding spell and by collecting the needed atoms. The player can talk with Carol, which is going to explain some climate change evidences, such as the impacts of climate change in animals and plants, and she is going to assign him the mission of filling the lake with water.

Again, the interactive tutorial is going to explain the process of creating a resource in the game. After the player fills the lake with water he can use the boat to leave the place. In this stage, the tutorial explained all the necessary steps to complete a game level, and the player is ready to play the second game level.

The boat trip leads the player to the other shore of the lake, where he starts the second game level.

The first obstacle that the player has to overcome is a closed cave, that does not have dioxygen. After the player collects the needed spell and atoms (by splitting a visible CO_2 molecule), he will have to create dioxygen to open the cave.

Inside the cave there are a chest, a portal, another CO_2 molecule and another door that faces the other side of the cave, leading to its exit. To open the door, the player needs to create a diamond resource, however both the spell and the diamond structure (needed in the spell to align the carbon atoms to form the diamond model) are hidden inside the chest, so the player will have to perform the AR activity by entering the portal to earn the key that opens the chest.

The second game level will be completed after the player creates the diamond and opens the door exit.

Table 3.1 shows all game levels content summarized and organized by items, build atoms AR activity, missions, climate change evidences and individual practices.

Note that as new levels are created, new content (more GHG molecules, chemical elements, missions and stories) can be easily added to the game.

Table 3.1: Summary of game levels content

	Game level no. 1	**Game level no. 2**
Magic objects	glasses, wand and multiplier	diamond structure
GHG molecules and Chemical elements	CH_4 and CO_2 - H (hydrogen), O (oxygen) and C (carbon)	CO_2 - O (oxygen) and C (carbon)
Build atom AR activity	build an oxygen atom	build a hydrogen atom
Missions	create water to fill the lake	create dioxygen to open cave entry and create diamond to open cave exit door
Climate change evidences (narrated in Carol stories)	impacts on animals and plants	decreased snow
Individual practices (narrated in Vinicius stories)	use energy wisely	consume less, waste less - 3Rs

3.4 Game Review

Some of the most important features of the game are the integration of AR and manipulation of physical objects allowing 3D visualization and manipulation of atoms and molecules. As we noted in Chapter 2, these characteristics have great potential for understanding abstract concepts, having already been explored by several researchers.

However, there are also characteristics that differentiate our game from the others.

Most examples presented in Chapter 2 didn't contain a playful component, and do not provide specific goals to the user, allowing them to freely explore the world of atoms and molecules. Others, although providing specific goals and challenges, present different features from our project. Almost all researched games did not used the mobile phone as the main device, requiring a lengthy system set-up. In the case of *Happy atoms* and *Periodic Fable*, despite using the mobile phone as the main device, these games require the use of physical objects which are harder to move around, comparing to cards which do not take up much space and can be easily stored in a small bag, in the pocket, or even between the back of the smartphone and its cover.

Our game also presents the three important levels of goals [67]: short-term (split the GHG molecules, collect the magic objects, spells and atoms), medium-term (perform the build atoms AR activities, open the chest, open the doors) and long-term (leave the place in the allocated time).

The conclusion of a game level also allows the player to grow in the game, unlocking new game levels with new items, stories and challenges, which works like a reward. That feeling of accomplishment fosters motivation and creates interest in the subject.

Finally, another feature that differentiates our game from others is the learning content, which is not exactly the same as the researched cases. Besides conveying chemistry

concepts present in the portuguese school curriculum, our game also connects those concepts with the climate change problematic provided by the story behind the game to awaken interest in chemistry and raise awareness of the problems of climate change.

As already mentioned, each player action on a game level is related with a chemistry topic. Table 3.2 summarizes the connection between the learning content of our game (that covers all chemistry concepts defined in section 3.1) and the game features that convey each topic.

Table 3.2: Learning content of our game and respective game features

Learning content	**Game features**
1. Understand the constitution and the model of an atom	Creating atoms of specific elements in AR activities, using particle cards (protons, electrons and neutrons)
2. Understand that molecules are present in our world, and each molecule is composed by atoms connected between them.	Creating molecules (e.g. the water molecule) and by splitting the GHGs
3. Know the name, the chemical symbol and recognize the atomic number of some basic periodic table elements (like Hydrogen, Oxygen and Carbon).	Through the use of cards in the AR activities and by viewing its name often in the inventory and in the spell book
4. Recognize visually the place of some elements in the periodic table	Visualization of the Periodic Table of Elements shelf
5. Recognize the formula of some molecules that are present in our world (water molecule, dioxygen) and some gases that contribute to the greenhouse effect (Carbon dioxide and Methane)	Creating molecules to accomplish missions
6. Recognize the molecular model of some molecules	GHGs - by viewing their constituent molecules before splitting; Water molecule and dioxygen - When creating the molecules in the laboratory and in AR activities
7. Distinguish molecules from macromolecules	Creating macromolecules (like diamond) to accomplish missions
8. Recognize the model of macromolecules	When creating the molecules in the laboratory and in AR activities
9. Understand that the world is suffering from climate change and recognize the GHGs (gases that are contributing to the greenhouse effect)	Through storytelling and by splitting the GHGs to use the corresponding atoms in order to create other “better” molecules
10. Provide prevention measures to soften climate change	Through storytelling
11. Other info (explaining concepts mostly)	Loading phrases and AR activities

It should also be noted that the fact that the game is individual allows the learning process to be adapted to each user, respecting each learning speed. In addition, the game

could also have an added importance during COVID times allowing for entertainment and learning when children are more isolated.

Finishing this section, Figure 3.31 shows the final game flow diagram, for a general and clear view of the whole game.

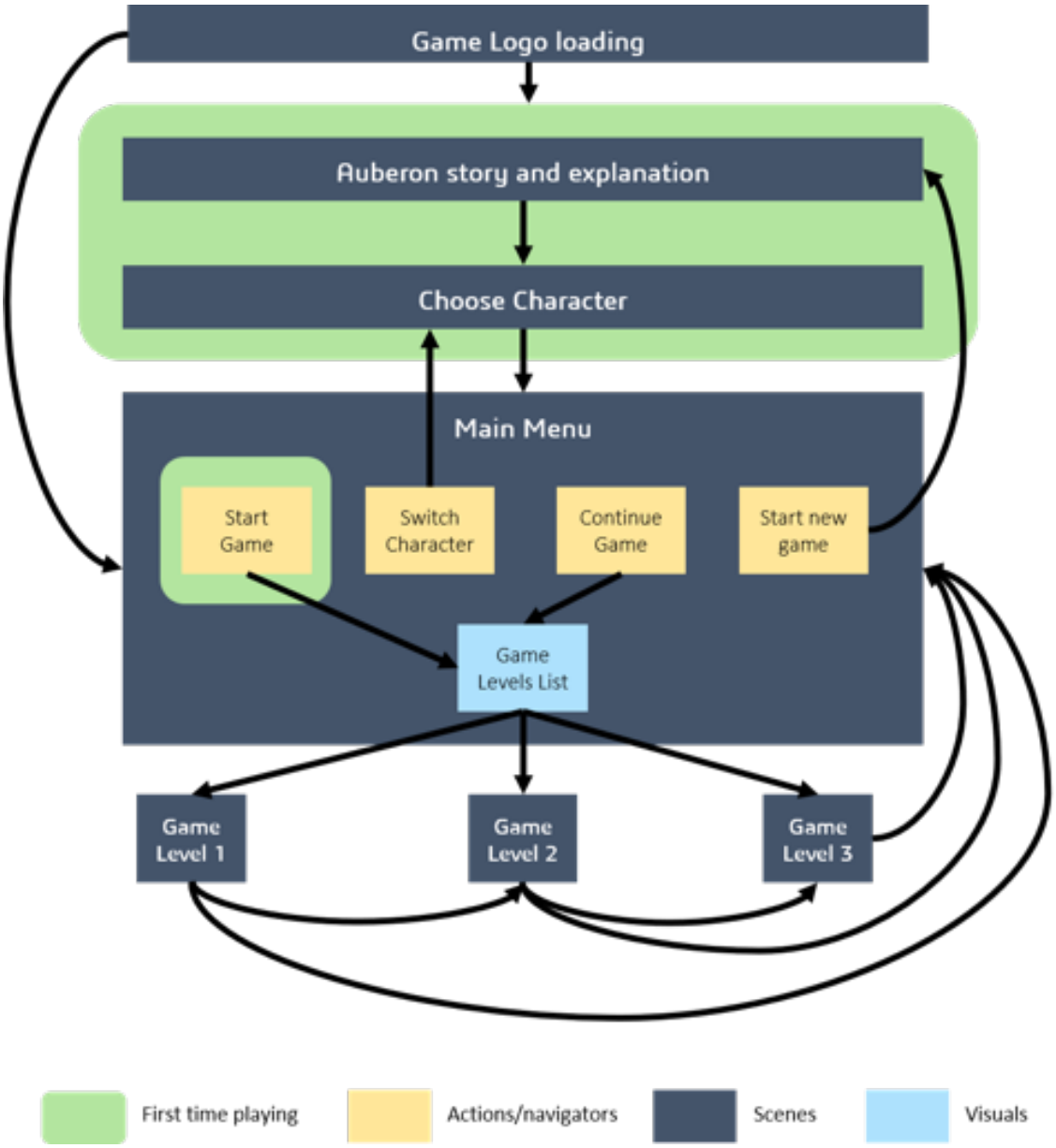


Figure 3.31: Game flow diagram

3.5 System architecture

This sub-chapter presents the chosen technologies and tools that are believed to be the most suitable for this work.

Figure 3.32 presents the game architecture, dividing the technologies and tools in four sections: design tools, AR platform, game logic and device.

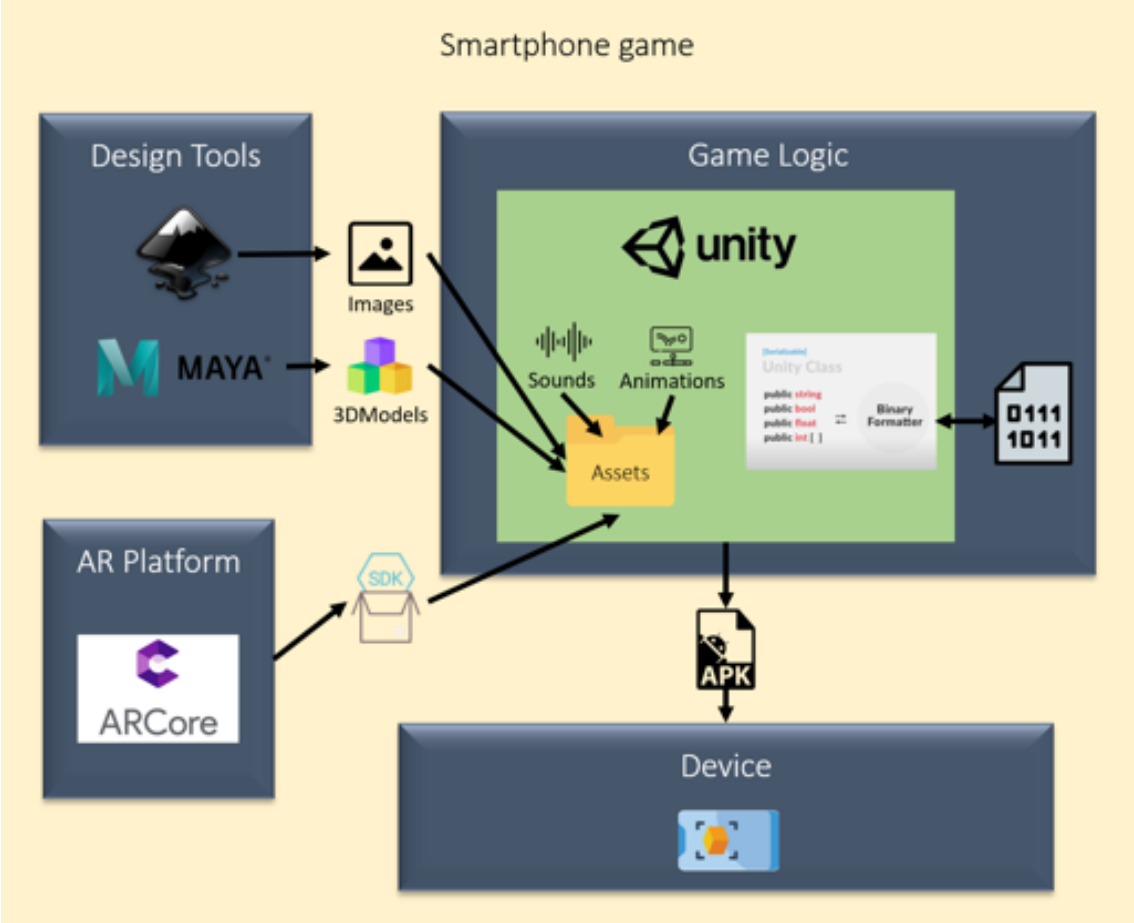


Figure 3.32: Game architecture diagram. This diagram has been designed using icons made by Freepik, Smartline, Flat Icons, Pixel perfect, DinosoftLabs, Darius Dan and Smashicons from Flaticon.com (accessed in February 2020)

Although this dissertation's work does not focus on the design of the characters and objects of the game, good visuals and graphics can help to improve the overall design, as well as making it more captivating for children.

There is a wide list of available libraries that provide quality assets. We gather some free assets we though that would make sense for our work, and we organize them in a way that everything seem to match.

However, there arose a need to create new assets, specially regarding the representation of some chemistry concepts, since some researched assets did not fit entirely our purpose.

We can divide all used assets into six groups: environment assets, properties, characters, sounds, animations and GUI (Graphical User Interface).

1. **Environment** - We created our own terrains (using the unity terrain tools) to make environments that fit the flow of the game. To paint the terrains we used free terrain

textures, and we filled the environment with available 3D objects such as mountains, water reflectors, doors, trees, and other details such as plants, crystals and VFX, that transmit a magic feeling. We also added some ambient music to each environment.

2. **Properties (abbr. props)** - The used portals were adapted by us, using a small door as the model, and we modified its texture to look more like a portal. The same was made with the physical cards, by taking an available model and modifying it using *Inkscape*. Prop assets such as the magic glasses, GHG molecules, atoms, 3D atoms models, the periodic table and most filters in AR activities, were created by us. Other props such as chests, wand, multiplier and others weren't modify or create ourselves.

3. **Characters** - we used available characters and adapt their animations to be used in different actions (e.g. when splitting a molecule, the player raises his wand).

4. **Sounds** - During our game there are several sounds, for example while splitting a molecule, creating a resource, opening a door or a chest, and many others. The sound files were all searched and chosen by us.

5. **Animations** - Excluding character animations, the others were all created by us using the unity animation editor. We also created several cut scenes (e.g. open door, open chest, collect glasses and show GHG molecules, ...), using the unity timeline and cinemachine.

6. **GUI** - We took advantage of the available 2D assets that made sense in our game, and created new ones like the game logotype, particles textures, 2D atoms, the 2D Bohr model with captions, and many others. Most of the used icons were obtained from Flaticon.com (accessed in February 2020) and made by Freepik (e.g. lock, star, key, dioxygen and wand icons shown in Figures 3.8, 3.9, 3.11b, 3.14a, 3.14c, 3.15a, 3.17, 3.21, 3.22 and 3.25), Good Ware (e.g. atom icon shown in Figure 3.12) and Smashicons (e.g. glasses icon shown in Figures 3.10b and 3.22).

To create our own assets, we used the following tools:

1. **Inkscape**[2] - an open source vector graphics editor distinguished by its use of Scalable vector Graphics (SVG) as the native format. It can be a good substitute of some more popular tools like Adobe Illustrator, Corel Draw, Freehand, or Xara X. Inkspace allows object creation and manipulation, presenting other features such as fill and stroke, operations on paths, text support, rendering and file formats.

[2]https://inkscape.org

2. **Autodesk Maya**[3] - software used to generate 3D assets, with powerful modeling, rendering, simulation, texturing and animation tools. Is freely available for FCT NOVA students and it is a more precised tool comparing to *Blender*[4].

Unity[5] was the chosen game development engine to implement our game. Besides supporting various devices (including smartphones), Unity is the preferred platform for creating immersive games, allowing the use of specialized extensions for AR.

One of these AR extensions is the **ARCore**[6], which was the chosen one for our game. This Google's platform uses motion tracking, environmental understanding and light estimation to integrate virtual content with the real world.

Unity is also an interesting platform for applications that aim to support multiple operating systems. Our game was developed for the Android platform, which is the mobile system with the largest existing market share [66]. In the future, we can easily create the game for iOS too. Finally, Maya objects can be easily imported to Unity, which is also a good advantage.

We decided to store the game data in custom **Binary files**. These can be an advantage comparing to Unity Playerprefs and JSON and XML files, since they provide a more secure option, considering that they are hard to read and be modified by third parties. By saving the player progress in Binary files we are storing data locally, which can also be advantageous taking into account that some users may not have network access in their homes (something we heard a lot on the news during COVID times), or other places. Besides, even if the users have network access, some parents may also don't want their kids to access it for security matters. This way, all users will have the opportunity to play the game, regardless their conditions.

[3] https://www.autodesk.com/products/maya
[4] https://www.blender.org/
[5] https://unity.com
[6] https://developers.google.com/ar/discover

Chapter 4

Design process and Implementation

This chapter presents the evolution of the game by describing the design process and the development iterations.

The design process was a long journey, and a lot of changes and improvements were made between the sketching phase and the final game.

In order to create the best game possible by improving the quality and functionality of the product and its interfaces, we decided to follow an iterative design process [13]. This methodology involves a cyclic process of designing, implementing and evaluating a product. Although it was not possible to perform some tests as we would normally would due to COVID prevention measures, we tried to have them tested in more informal ways, as we will explain better throughout the chapter.

There were four main design stages throughout the design process: sketching, first prototype, second prototype and the game development.

4.1 Sketching

As already mentioned, this thesis was originally thought to be a collaboration with the project *Periodic Fable*, and, although we eventually followed different paths and carried out projects with different characteristics, this collaboration was part of the design process in the sketching phase, serving as a starting point for our work.

At the beginning of the sketching phase (around November 2019), the *Periodic Fable* project still didn't address the sustainability topic, however the flow of the game didn't change much besides that. At that time Sandra's goal was to find a way to connect the original project with the climate change problematic.

Then, we both started thinking about ways to fit the climate change problematic into the game. Sandra also provided a document that contained a list with some design issues

identified in a heuristic evaluation, so I also started to think about some ways to fix them.

I've done several formal and informal chemistry game researches at the time, and some new ideas started to emerge.

Firstly I started by learning more about the climate change problematic - its causes, evidences and solutions.

Since the main goal of the *Periodic Fable* game was to create molecules to accomplish tasks and overcome the obstacles along the way in the second part of the experience, I thought that it will be interesting if the player could somehow split available GHG molecules and use their corresponding atoms to create new molecules (see Figure 4.1), instead of creating them by choosing the correct atoms in an available list.

Quickly the magic theme idea pop up, since it seemed to present many advantages in terms of interaction as explained in section 3.2.

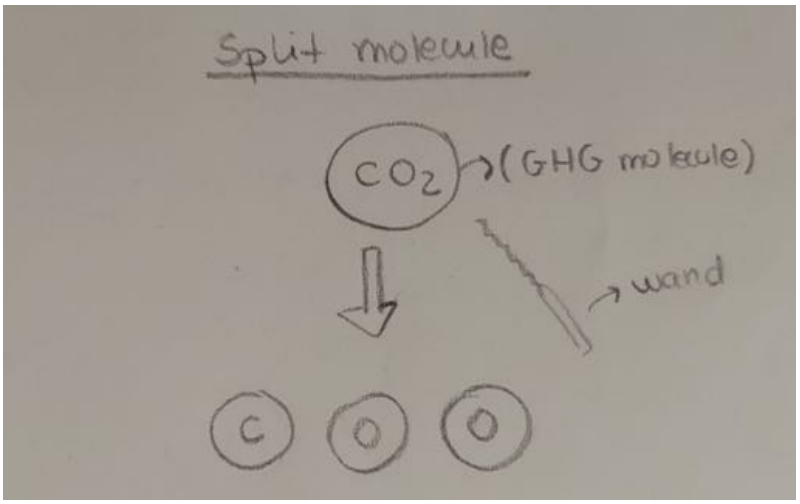


Figure 4.1: Split molecule sketch

One of the design issues presented in Sandra's document results was that the technology didn't allow to scan the cubes to gather the creatures when in the 3D world environment. Then, I started thinking that it could be interesting if the players used cards (see Figure 4.2) to combine the atoms and form molecules in augmented reality.

Other pointed design issue was "the screen with the creatures collected needs to show the formula used to overcome the obstacles", which could be easily fixed by using magic spells that correspond to the needed atoms to form a certain molecule (see Figure 4.3).

In late November 2019, we had a face-to-face meeting with Sandra and Prof. Valentina Nisi, Sandra's PhD advisor together with Prof. Teresa Romão, where we presented our ideas and we were able to test and better understand the concept of the *Periodic Fable* game.

Although we supported each others ideas, they couldn't be implemented together, so we decided to develop different projects with the same goal but different approaches. The idea was to continue working in collaboration by trying to create similar user tests and see how the different approaches influence the user experience.

Figure 4.2: Oxygen card sketch

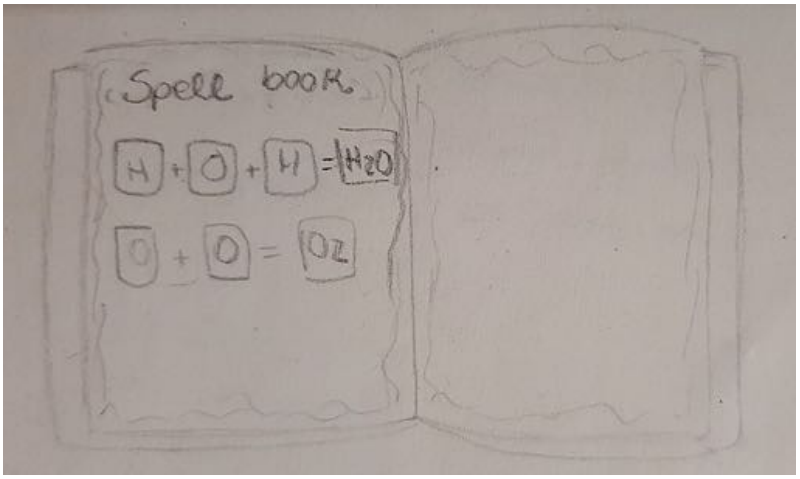


Figure 4.3: Spell book sketch

4.2 First prototype

Around January 2019, a first prototype was created in order to organize and represent the most recent ideas at that time and to possibly be tested informally with a small sample to point out bigger design issues before testing the actual prototype with users that fitted our target group.

The prototype was made using PowerPoint, since it allowed us to include animations to show the interface dynamics and represent AR in an easier way comparing to paper prototypes. We used online available cartoons to represent the characters and Sandra's 3D world, since our own designs were not completed at this stage.

The main ideas that were formulated at this time and remained in the final game were the following:

1. The player should use magic glasses in order to see atoms and molecules, since these are non-visible in the real world
2. To split the GHG molecules, the player should use a magic wand, so that he knows there is no way he can manipulate molecules and atoms in the real world, where there are no such magic powers
3. In order to form a molecule, the player should firstly gather the atoms that form the molecule from an Periodic Table of Elements shelf, in a place we called laboratory

We can also point out the following differences from this stage to the final game concept:

1. There was only one big world with various obstacles, as shown in Figure 4.4
2. As the player performs actions and grows in the game, he gains experience (xp), and he levels up when the xp bar is filled
3. The player can buy environmentally friendly items (e.g. an ecological car) in the game by creating and earning diamonds
4. The atoms are combined using cards in an AR activity and it shows the Lewis structure of the molecule that is being formed (see Figure 4.5)
5. Player missions correspond to individual practices

In section 4.4 we explain why some of these features were reformulated or cut off.

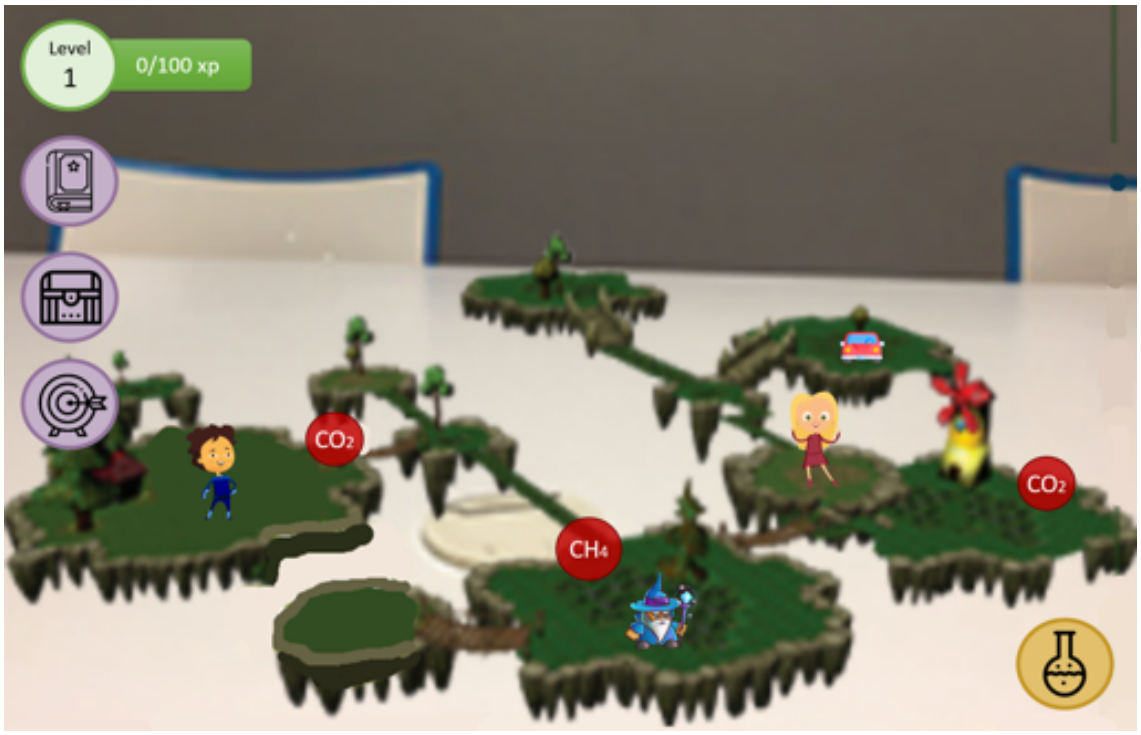


Figure 4.4: World of the first prototype. Icons by Freepik from Flaticon.com (accessed in February 2020). Player and Carol characters designed by macrovector from Freepik.com (accessed in February 2020)

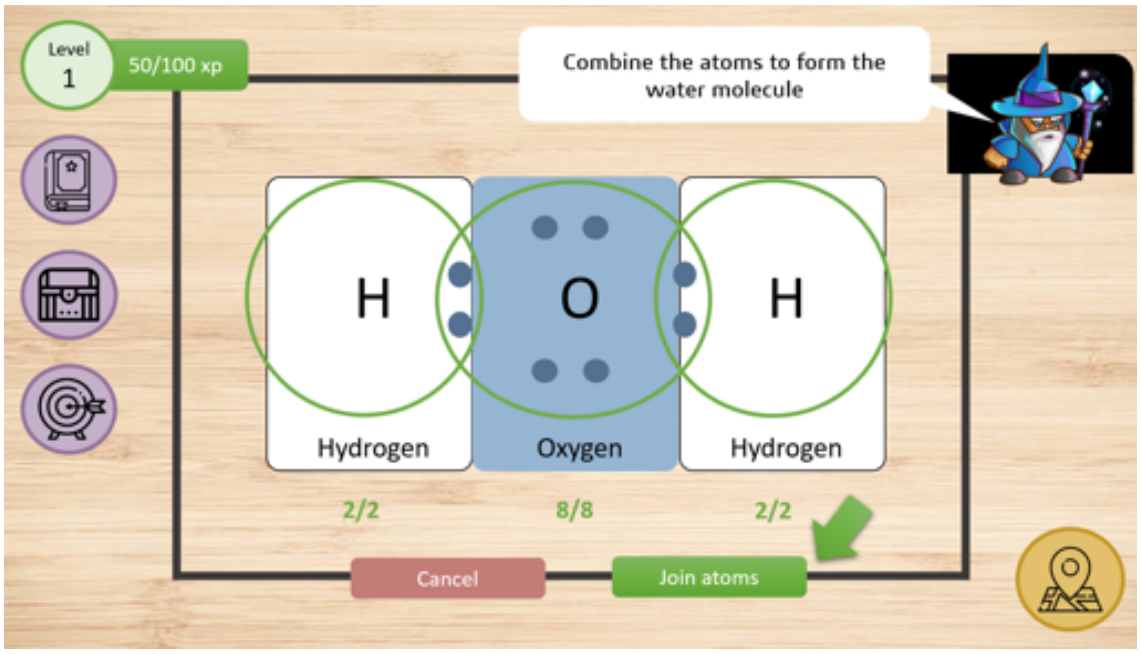


Figure 4.5: Creating a molecule in the first prototype. Icons by Freepik from Flaticon.com (accessed in February 2020)

4.2.1 Informal tests

The first prototype was tested informally with a small sample (5 users, which is the number of users recommended by Jakob Nielsen during formative, qualitative usability testing [49]).

The users highlighted different usability issues such as:

- non obvious buttons
- the tutorial arrows to indicate the next step needed to contrast to the background to make it more obvious
- the dimension of the story before the tutorial starts needed to be filtered so that users don't get bored and skipped it

These pointed out issues helped us to create the second prototype which was meant to be tested with more users that belonged to our target group.

4.3 Second prototype

After having some feedback from the first prototype, we decided to create a second prototype using the Marvel app[1], since it would allow us to test the prototype using a smartphone, which is the main device of the final game.

Besides improving our interface using the feedback from the first prototype to make it more understandable, not many changes were made in this stage regarding the concept of the game, except that this prototype contained our own 2D characters (see Figure 4.6).

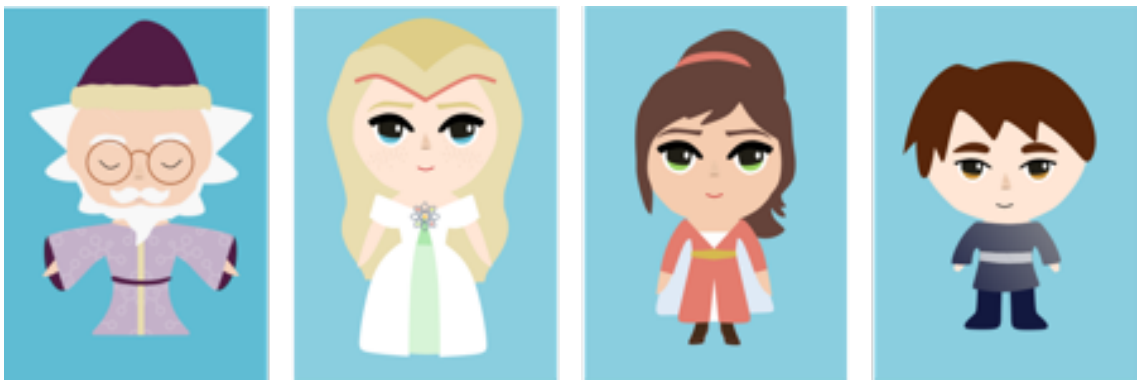


Figure 4.6: Designed characters for the 2nd prototype - Auberon, Carol, female player character and male player character

By presenting our own designed characters in this prototype, we could evaluate how much users liked it. However, this stage happened in the beginning of March 2020, and, unfortunately, the prototype, despite having been fully made, was not possible to be tested with children of our target group due to COVID-19 safety measures.

[1] https://marvelapp.com/

We ended up by choosing different character designs for the final game, since we realized, after better analysing our target group and their preferred mobile games, that our characters could be a bit childish for them. This way, and since we couldn't perform tests in this stage to get valid results, we decided that the final characters we came up with were the safest option.

4.3.1 Analysis with a chemistry teacher

We thought it was important to make sure all chemistry concepts were corrected and were well approached, not leading to misinterpretation by users, before we move on to the supposed second prototype testing phase. Then, we contacted a trusted chemistry teacher that analysed our approach and game concept during the second prototype development.

The teacher stated that the game was a really interesting idea with good potential and she liked the concept in general. Despite all, the teacher point out the following issues related with some chemistry concepts:

- When creating a diamond resource, it is required to distinguish this resource, which is a macromolecule, from other resources that are molecules, like O_2.

- The Lewis structure may be too complex for children, since they will only learn it in high school if they chose a scientific area, although the way we were presenting the concepts in the game did not require them to know about it or do complex actions, and it only served for them to see how the atoms joined together.

Although we couldn't do users tests afterwards, as explained before, these information was crucial to create a well-approached chemistry game. After this, we proceeded to the game development.

4.4 Game development

COVID-19 not only didn't allowed us to perform 2nd prototype tests, but it was also an obstacle during the development and evaluation of the game. The collaboration with Sandra's project also became difficult since it was hard to test each other's games remotely and be aware of each others improvements in due time.

When starting the development of the game, the augmented reality parts could not be tested since we didn't had equipment suitable with the used AR technology. Note that, to be tested, AR unity scenes need a compatible device to access the camera and perform AR algorithms.

However, we decided to adapt our game development tasks, and advance in what we could. The first decision made was to create the game levels out of the AR environment. This turned out to be a great decision since, besides allowing us to start the game development while we wait for the equipment, the motion tracking of ARCore is not 100 percent

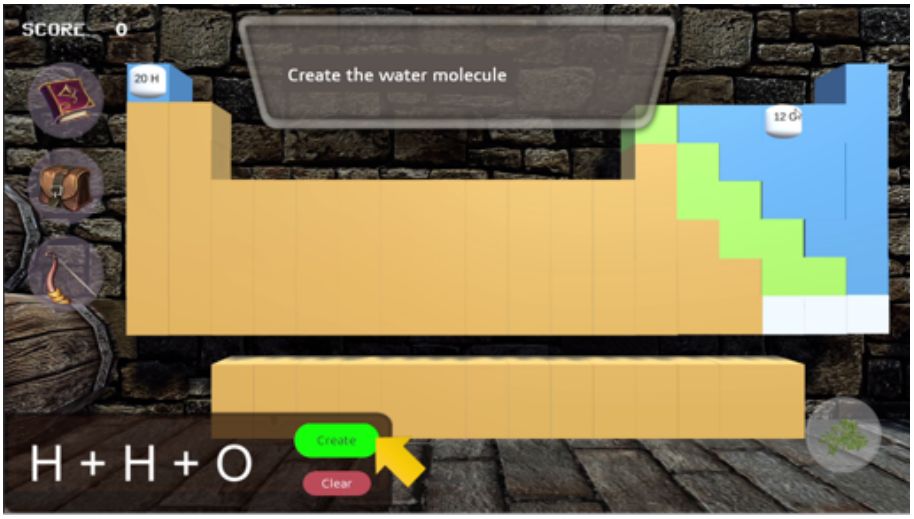
precise, and the world will most likely always be moving, so users could definitely struggle with it, contributing to a tedious experience. Anyway, the AR potential would not contribute in this part, making more sense in the visualization of atoms and molecules.

Throughout the game development process some other changes and improvements were made, both in terms of graphic design (see Figure 4.7), and gameplay:

- One big world may not be the best approach when comparing with having separated game levels, since it will not give a mystery and accomplishment feeling - the whole world is visible and the players know what's next and what to expect, and they will not feel the same accomplishment feeling comparing to unlocking new game levels with unexplored environments.
- Since the Lewis structure may be to complex for children, we decided to cut it off and create new AR activities that took advantage of the AR potential, both for learning and motivation purposes: build atoms using physical cards, visualization of a molecule and macromolecule model, and the face filters.

Other improvements were made during the game development, resulting from intermediate tests. Of course, due to COVID-19, the evaluation phase wasn't how it would normally be. However, we did manage to test the game several times with a 13 year old boy, who provided crucial information, has detailed in the next section.

(a) World's first version. Icons by Freepik from Flaticon.com (accessed in February 2020)



(b) Laboratory's first version

(c) World's old version

Figure 4.7: Images of the first game versions

4.4.1 Intermediate tests

In July 2020, when COVID-19 measures already allowed us to contact with some more people taking the necessary precautions, we started to perform intermediate tests with a 13 year old boy. We had around 4 testing sessions in total.

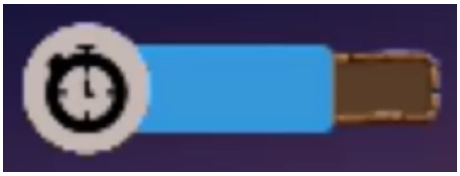
Table 4.1 summarizes the main issues found during these sessions, and respective solutions.

Table 4.1: Issues found and respective solutions

Issues	**Solutions**
The movement control was too slow, and the Lemuria place was too extensive, taking a lot of time to get to the items and perform actions	Increase movement speed and decrease the space
When collecting the glasses, it wasn't obvious that the GHGs appeared and consequently he couldn't realize that the magic glasses were the thing that allowed the visualization of the GHGs molecules and corresponding atoms	Use cut scenes to draw attention to the magic glasses being putted on the character and to the GHGs that appeared consequently
He couldn't realize he collected some items and the purpose of each of them	For each collected item, besides appearing a panel with the description of the item (see Figure 3.10b), the storage also notifies when something new is collected
The game levels weren't that challenging, specially because he will always win the game sooner or later, only increasing the level experience	Add a time counter to complete each game level, decreasing the time for higher game levels, making the game more challenging to keep the player interested in the game. Note that, although being challenging, the game levels had a balanced difficulty level (not too easy nor too hard)
It could be relevant to motivate the players to repeat a game level to review some concepts in that game level. Although the participant wanted to repeat the game levels, his motivation was to try to give the right answer to all questions of the questionnaire, and it wasn't exactly related to the game, that didn't contain any purpose to repeat the game levels	Add a star score system, attributing a score when a game level is completed, and give the player the possibility to repeat a game level in order to increase his score

Regarding the time counter, it was first designed as a bar time counter (as shown in Figure 4.8a), however it didn't give a clear idea of how much time was left. Then, we decided to use a clock time counter (as shown in Figure 4.8b), where the time left was explicit.

We also did a pretest and posttest to evaluate some acquired knowledge in the first session. Although the participant already learned some concepts addressed in the game,



(a) Bar time counter. Clock icon by Freepik from Flaticon.com (accessed in February 2020)

(b) Clock time counter

Figure 4.8: Time counter design versions

he couldn't remember some of them in the pretest, such as the formula of some GHGs molecules, the difference between molecules and atoms, the atomic number of some elements and its position in the Periodic Table. However, in the posttest, he gave the right answer to almost all questions, and wanted to try the game again to answer the ones he wasn't sure or didn't remembered. Afterwards, he manage to get all the answers right.

4.4.2 Reanalysis with a chemistry teacher

As already explained, the game suffered many changes and improvements from the first prototype to the final version, both in terms of addressed concepts and gameplay. Then, we thought it was important that some concepts and the approach were reviewed by a chemistry teacher, who knows the scholar content, appropriate for the target users, before the final testing phase.

We could gather the main following observations:

- Regarding the concepts, the chemistry teacher stated that everything was correct and that we didn't need to modify anything.
- We are not introducing complex concepts for our target group, but we are already drawing attention to important details (the concept of an atom, the difference between atoms and molecules, among others).
- Before children have chemistry in the 7th grade they can play the game and see that chemistry can be fun and that they can "play" with it, helping to demystify the idea that chemistry is a hard field.
- The game allows them to understand the concepts rather than memorizing them.
- If they play the game they will capture some concepts and acquire some knowledge throughout time.
- As a teacher, she would advise 7th graders to install the game since she thinks that it will encourage them a lot to learn about the subjects.

- Some 7th year test questions could be answered with the concepts covered in the game, and some even later (such as the atom configuration and the molecules 3D model in the 8th grade).
- The game allows the kids to already get the idea of the Periodic Table, "that huge and very strange thing for those who didn't learned it yet".
- The game can be extended to other ages in the future, and it would be very interesting if that happened.
- "It's a good game, didactic, no doubt".

After reviewing the concepts covered in the game and the game itself with the chemistry teacher, as well as making sure everything was scientifically correct, we were ready to carry out the final assessment.

Chapter 5

Evaluation

This chapter describes the final tests performed on the final game version, ending by presenting its results.

In order to test the game effectiveness, we conducted a final test with some users that belonged to our target group (9-12 years old children).

Given the current COVID-19 situation, we could not perform the test as first planned. Instead of having school testing sessions, we had to find individual users that fit our target group and that were available and willing to test the game.

We did try to find at least one user of each age (9, 10, 11 and 12) and we were also careful to find users that had different profiles regarding other aspects such as how often they play, how comfortable they were with using a smartphone and their current school performance.

5.1 Evaluation goals

The main goals we intent to evaluate were:

- Attitude change regarding the chemistry field - generate motivation and demystify the idea that chemistry is a hard field
- Acquired knowledge - children should retain some knowledge regarding the topics addressed in our game
- Behaviour regarding the climate change problematic - sensitize children for the climate change problematic and create a desire to implement small environmental friendly practices in their daily routines

In order to evaluate these, we created our own evaluation model, inspired in the one proposed by Rafael Savi et. al [64], but adapted for our own purposes. We associated

the three main goals with three evaluation categories that follow important researched models: Reaction (level 1 of Kirkpatrick's model), Acquired Knowledge (BLOOM) and Behaviour (level 3 of Kirkpatrick's model). Figure 5.1 presents the structure of our model. Since the Kirkpatrick's model leaves open the parameters that should be evaluated, we decided to include the ARCS model to evaluate the motivation level, and some game user experience parameters withdrawn from the Savi et al. proposed model. Besides evaluating the general motivation and game user experience, we also included the reaction specifically in terms of the used technologies, and specific game functionalities, such as the score system used.

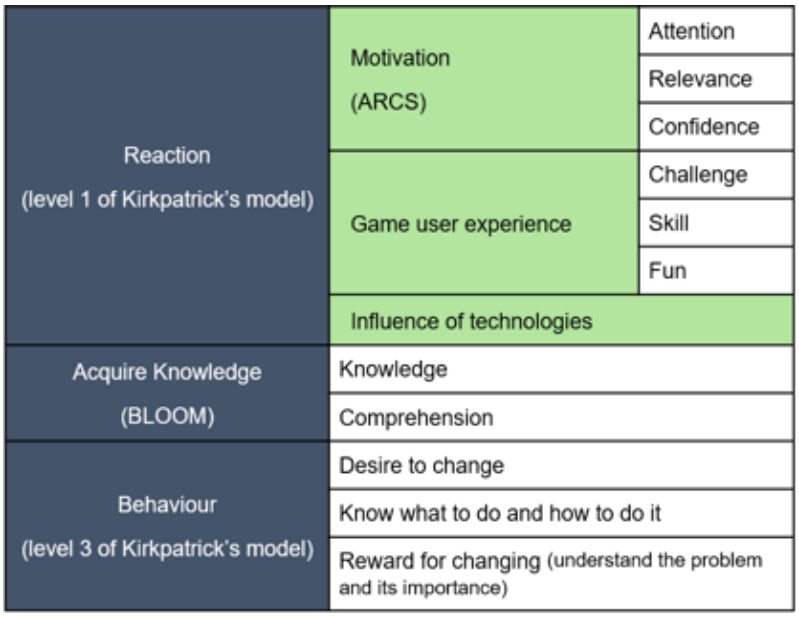


Figure 5.1: Structure of our evaluation model

Note that, in order to evaluate an attitude change regarding the chemistry field, as well as the acquired knowledge and behaviour regarding the climate change problematic, we add to perform a pretest and a posttest, to compare the differences before and after the participants played the game.

Since the evaluation is obtained by the participants, we created a questionnaire (presented in Appendix B), using Google Forms[1], in order to collect the data regarding the parameters of our model. However, besides evaluating the parameters of our model, we also created questions regarding the relationship of the participant with the used technologies, before they play the game, in order to understand if that could cause any difference in the results.

We were also careful to create a questionnaire adapted to our target group, using a non complex language in the questionnaire and some instruments from the *Fun Toolkit* [60] such as the smileyometer, with different scale rating methods (including the 5 Degrees

[1] https://www.google.com/forms/about/

of Happiness [26]) and the Fun Sorter. Another effective method that we opted by using was creating discussion of rationale [27].

As the questionnaire intends to evaluate many components, it became a little long. Then, we decided to divide the questionnaire into sections, showing only one at a time, so that the participants didn't get frustrated seeing a great amount of questions. Note that, since the questionnaire is filled before and after the participants play the game, it also helped it to seem shorter.

5.2 Methodology

When recruiting children to participate in a study, there are some things to have in consideration [59]. Before the actual testing phase, we add to create an authorization document to be signed by the children's guardians to allow their participation in the study, and optionally let the sessions be recorded, so that we could cite interesting comments and collect game interaction images.

The testing sections needed to be in person to test the interaction of the participant with the AR technologies and tangible objects.

As already mentioned, before the participants played the game, they add to perform a pretest to understand their relationship with the used technologies, evaluate their previous knowledge and attitude regarding the chemistry field an the climate change problematic. In order to do not demotivate the participants for not knowing the answers regarding the previous chemistry knowledge, before the pretest we explain them that it was ok if they do not know the answers and that that was actually what we expect to happen at their age.

Then, after the pretest, the participants were asked to play the game, followed by the posttest. Each session lasted about one hour in total.

Note that both the game and the questionnaire had to be in portuguese, so that the participants could understand them and give credible answers.

Figure 5.2 shows the set-up of the system during a testing session.

Figure 5.2: System set-up

5.3 Results

This section presents the results of the tests, organized by subsections. Some results are visually accompanied in this section by the respective graphs and/or tables for a more specific view of them. However, all the results are attached in Appendix C.

5.3.1 Participants' profiles

As already mentioned, we were careful to find participants with different profiles, so that the results were as rich as possible. Sections 2, 3 and 4 of the questionnaire present the questions regarding the participants' profiles.

We tested a total of 8 children (5 boys and 3 girls), where four of them were 10 years old (5th grade), two of them were 12 years old (7th grade), one of them was 11 years old (6th grade), and, lastly, one of them was 9 years old (3rd grade).

Note that the tests were performed in early November, so the 12 years old children hadn't learned yet the chemistry part, since they start the 7th grade with physics.

Regarding their experience with technologies, we could notice that these influenced their interaction with the game - children who often play in the smartphone easily played the game, unlike others that had more difficulty but recovered easily throughout the game. The same was noticed in the AR activities.

Although the previous experience influenced their interaction, the same cannot be said regarding the acquired knowledge, which had very positive results, as we will explain forward.

We also verified that most of the participants (seven - 87.5%) have their own smartphone, which operating system is often (62.5%) an Android. Although almost all of them (five - 62.5%) stated that they had internet with good quality, three of them didn't, and two of those three also stated that they didn't have network access in all home rooms. One of the guardians that currently has quality network also had to recently install an extra equipment to have network access in all house places.

5.3.2 Reaction

This section presents the results of the category that seeks to assess students' reaction.

MOTIVATION (Section 10 of the questionnaire)

Attention

This parameter intends to evaluate aspects related to obtaining and maintaining user's attention.

Results suggest that the game's graphic design really captured participants attention, receiving a mean score of 4.50 (using the 5 Degrees of Happiness SFL) with a standard deviation (SD) of 0.76.

All participants understood the game goals which were finding an exit before the time ends (long-term goal) by creating water, dioxygen and diamond (medium-term goals).

Relevance

The relevance of the game, specifically in terms of importance and usefulness, was rated with a score of 5 by all participants. When faced with the question "why?", all participants pointed out that the game helps them to learn new things, with some of them (four children - 50%) specifying that it teaches important subjects such as chemistry and how to fight the climate change problematic.

Confidence

This parameter focus on providing sensations of progress to the player, by evaluating its degree of difficulty in understanding and performing some tasks.

Most participants (five of them) struggle a little when using the control to collect the atoms (see Figure 5.3), since it requires a more precise action in terms of player movement.

We also notice some of them tried to directly click in the items to collect them or perform other actions instead of moving the player using the controls to get close to them to perform those actions.

The users testers also pointed out that they spent some time remembering how to go to the lab to create a resource. Even though the tutorial explained them the whole process, it wasn't enough for them to remember it easily.

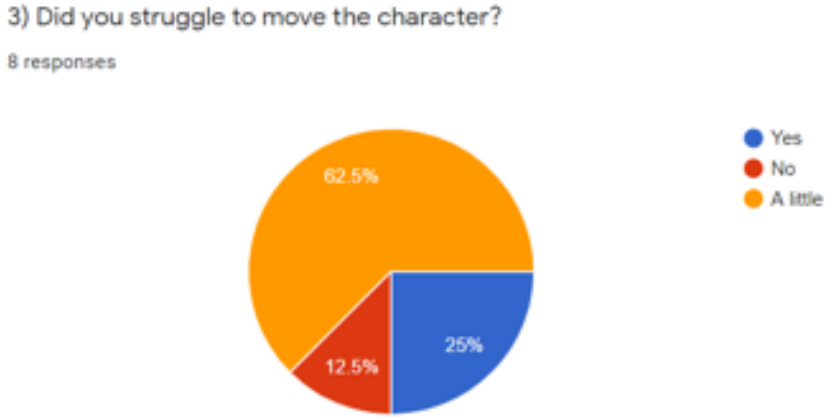


Figure 5.3: Questionnaire results - Section 10 question 3

User experience (Section 11 of the questionnaire)

Challenge

In terms of challenge, participants rated their willingness to continue playing the game with a mean score of 4.38 and a SD of 0.89. The majority of them (five participants

- 62.5%) also wanted that the game had more levels to keep playing, while the others answered with a "maybe".

Skill

Almost all participants won the first game level in the first attempt, however they could only won the second game level in the second attempt (see Figure 5.4). Note that the second game level presupposes the creation of two resources at about the same time as the first level, where players only create one resource and had the help of the tutorial. They also took more time in the second level since, as already mentioned, they couldn't remember how to go to the lab to create a resource. As soon as they realized where it was, they easily finished the game level.

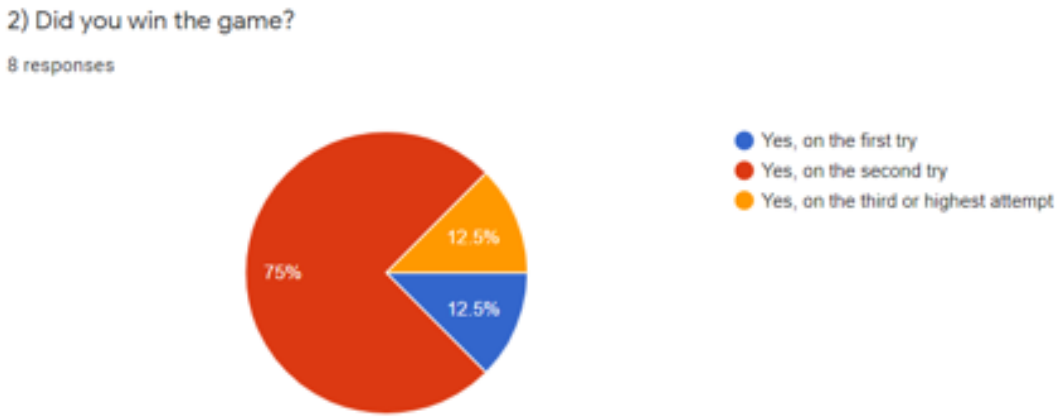


Figure 5.4: Questionnaire results - Section 11 question 2

The game also promoted a positive attitude regarding the chemistry subjects, with an average improvement of 1.38, showing that the users felt more successful with the game (see Table 5.1). We also notice that the idea of chemistry being difficult mainly came from older schoolmates' comments.

Table 5.1: Attitude change regarding the chemistry field

	Ranking mean (scale 1 to 5)	**SD**
Pretest (section 5 question 2)	3.12	0.99
Posttest (section 11 question 6)	4.50	0.76
Improvement	1.38	1.18

Fun

The participants rated the fun of the game with an average score of 4.38 and seven of them (87.5%) wanted to play the game again, some just for the fun of it (25%), and others

because it was fun to learn about chemistry and the climate change problematic (62.5%). The remaining participant (12.5%) answered with a "maybe".

Influence of technologies (Section 12 of the questionnaire)

We used the *Fun Sorter* [60] in order to understand which activities the participants liked the most. However, the results were very dispersed, as shown in Figure 5.5. Table 5.2 shows the mean and standard variation of the top place (1, 2, 3 or 4) of each activity.

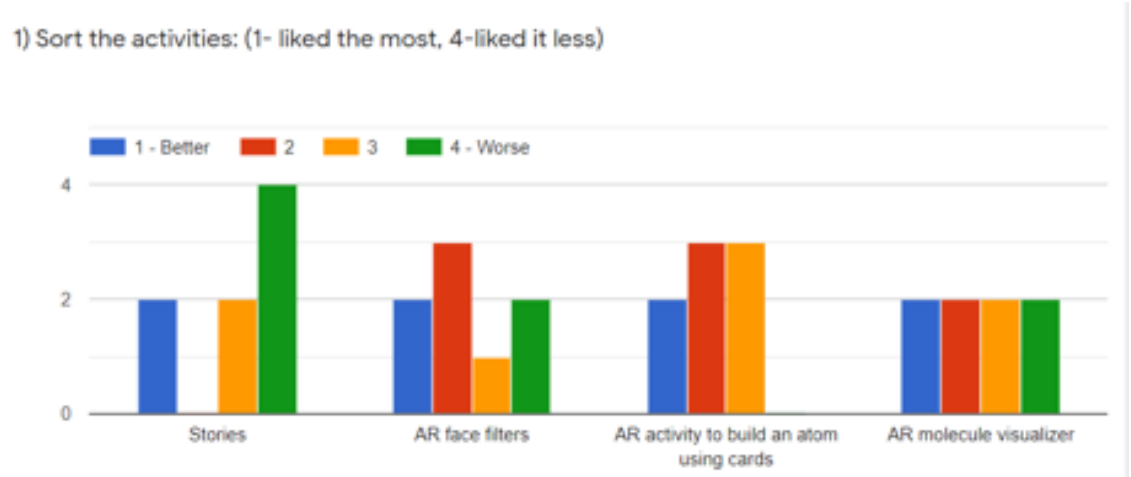


Figure 5.5: Questionnaire results - Section 12 question 1

Table 5.2: Mean and SD of each activity

	Mean	**SD**
Stories	3.00	1.31
AR face filters	2.38	1.19
AR activity to build an atom using cards	2.13	0.83
AR molecule visualizer	2.50	1.20

Looking at Table 5.2, that provides a better view of the top place of each activity in general terms, we can see that stories were the least liked activity, followed by the AR molecule visualizer. This makes some sense considering that these activities were the most passive, with less control by the players. We notice that girls were the ones who liked the filters the most, comparing to boys. Finally, the most liked activity was the AR activity to build an atom using cards, which is the most complex activity in terms of player actions, but it is also one of the most important activities in terms of learning content since, as stated before, it teaches the atomic structure of an atom.

Most participants (five of them - 62.5%) claimed to have a better 3D visualization in the AR molecules activity comparing with the AR activity to build an atom using cards.

Those children stated that the only reason they felt they had a better visualization in the AR molecules activity was because the 3D objects were larger. Even so, three participants (37.5%) claimed that they preferred to use the cards and had a better visualization for being able to rotate and move the atoms in the AR activity to build an atom.

Regarding the 3D visualization using augmented reality vs. using a paper image, all participants stated that it was easier to visualize and understand them using AR.

The participants showed a great desire to repeat the game levels to obtain high scores, with a mean of 4.75 and a SD of 0.71.

5.3.3 Acquired knowledge

In order to evaluate the educational effectiveness of the game, we had to test the knowledge of the participants before (sections 6, 7 and 8 of the questionnaire) and after (sections 13, 14 and 15 of the questionnaire) the game. We did this by asking them questions that address the learning content specified in Table 3.2. For each question, a score was attributed, giving one point for a correct answer and zero points for a question they didn't know or remembered or that was incorrect. The final scores were converted in percentages to facilitate the analysis of the results.

Although it is not supposed that children acquire so many knowledge by playing just one time, we wanted to understand if there is already an improvement in those conditions.

Note that, before playing the game, we advise participants not to make an effort to understand or memorize any concept introduced in the game, but that instead they play the game like any other. This way, we could better understand what they really captured naturally when playing the game.

The results, summarized in Table 5.3 were very positive and showed a significant improvement between the pretest and the posttest.

Table 5.3: Summary of acquired knowledge

	Mean	**SD**	**Lowest**	**Highest**
Pretest	10.7%	6.8%	2.4%	24.4%
Posttest	59.2%	20.9%	26.7%	86.7%
Improvement	48.5%	18.2%	21.8%	72.0%

In the pretest, most of the participants knew that chemistry was a school subject and, although none of them knew the concept of an atom and a molecule, 5 of them (62.5%) recognized the water chemical formula (H_2O) and the name of some atoms such as the oxygen and carbon was recognized by 2 of them (25%). In general, the children did not know almost anything about the subject before they play the game.

All of the participants improved their knowledge after they played the game, ones more than others, but they all obtained higher grades in the posttest.

Figure 5.6 presents the percentage of global answers in each question marked with a color applied by a progressive color scale, that goes from red (low score) to green (high score). This allows us to get a clear view of which questions children had more difficulty to understand and consequently which game features should be improved. It also clearly shows that posttest results were much better than the results of the pretest.

Section	Question	Pretest mean score	Question	Posttest mean score
Acquired knowledge Part 1	S6 -1	20,0%	S13 -1	70,0%
	S6 - 2	0,0%	S13 - 2	62,5%
	S6 - 3	16,7%	S13 - 3	91,7%
	S6 - 4	0,0%	S13 - 4	66,7%
	S6 - 5	50,0%	S13 - 5	75,0%
	S6 - 6	12,5%	S13 - 6	75,0%
	S6 - 7	0,0%	S13 - 7	50,0%
Total		**16,5%**		**73,8%**
Acquired knowledge Part 2	S7 - 1	2,1%	S14 - 1	39,6%
	S7 - 2	0,0%	S14 - 2	58,3%
	S7 - 3	0,0%	S14 - 3	91,7%
	S7 - 4	4,2%	S14 - 4	58,3%
	S7 - 5	2,5%	S14 - 5	37,5%
Total		**1,8%**		**52,5%**
Climate change	S8 - 1	0,0%	S15 - 1	37,5%
	S8 - 2	62,5%	S15 - 2	100,0%
Total		**31,3%**		**68,8%**

Figure 5.6: Summary of acquired knowledge in each question and respective section

5.3.4 Behaviour regarding the climate change problematic

According to the pretest (section 8 of the questionnaire) answers, only three (37.5%) children had an idea of what climate change is, pointing that it was a bad thing. Of the remaining five, two (25%) of them stated that they already heard about it but didn't know what it was, one (12.5%) of them though that climate change was a good thing, and the remaining (two children - 25%) stated that they didn't know what it was.

The following points present the results of the posttest (section 15 of the questionnaire), where we notice an improvement regarding the knowledge of daily individual practices to fight climate change and a greater concern for this problematic on the part of the participants.

Desire to change

In order to evaluate the desire to change by contributing with small practices to fight climate change, we used the 5 Degrees of Happiness SFL, and all participants showed a strong desire to contribute for change by giving a rating of 5.

Know what to do and how to do it

In the pretest, only five (62.5%) of the participants could already point out some daily individual practices to soften climate change. However, in the posttest, all participants knew what were the practices, reported in Vinicius's stories, giving 100% of correct answers.

Reward for changing

To evaluate this parameter, we wanted to examine if the participants were aware of the climate change consequences and if they understood the importance of fighting it.

Four (50%) of the participants remembered some climate change consequences reported in Carol's stories, while others (50%) didn't.

Regarding the importance to fight climate change, in the pretest the ranking mean was 3.50 with a SD of 1.69, while in the posttest all participants attributed a ranking of 5, with a mean improvement of 1.5.

5.3.5 Observations

During the tests we could notice that the participants were enjoying the game as well as understanding the concepts, and we could hear some comments such as "Oh, so this is what (some concept) means!", showing satisfaction for being able to understand it. One of the children was so involved in the game that he completely abstracted himself from the real world.

Regarding the questionnaire, taking into account that children often give answers according to what they think would be more pleasing to the person in charge, we made sure they knew it was fine to not like something or understand something and that we really wanted them to be sincere.

We notice that the participants who usually play used their favourite games as a benchmark for evaluating our game, particularly in terms of graphic design and fun. We heard some comments such as "the graphic design was really good, however I've seen better ones with better resolution that use improved technologies, so I'm going to rate the graphic design with a 4 (out of 5)". This was very positive since they were including our game in the set of games they liked to play, instead of putting ours aside.

One of the 12 years old participant that is currently on the 7th grade also stated that he thinks his chemistry teacher would like him and his colleagues to install the game, when they learn the chemistry part at school in the future. He also stated that the game

was really well-though and all game parts matched well with each other and everything in the game made sense.

In the end of one of the test sessions, the participant willingly played the game for the second time and improved his score in both game levels, obtaining a high score in the first game level (three stars) an a medium score in the second game level (two stars).

Some parents even commented that the game was a great initiative and that they wanted their children to have access to it because it was educational and it made their kids feel like they really could learn more about the subject.

Finally, all participants stated that they want to install the game when they are learning the chemistry concepts addressed in the game at school to complement their study while having an entertaining experience.

Chapter 6

Conclusions and future work

This chapter describes the conclusions drawn from our work, discussing the results obtained in the final tests. Finally, it presents the future work to improve our solution.

6.1 Conclusions

Even before children approach chemistry as a school subject, the idea that many of them have, often generated by comments from older schoolmates, is that chemistry is a difficult field.

The creation of educational games based on AR and TUI has been increasingly explored by researchers, whose results are very positive. In current times, older children have close contact with new technologies, and some even already have their own smartphone.

Then, in order to promote motivation regarding the chemistry field and taking advantage of its relation with climate change, which is also an important subject to be conveyed for the future of humanity, we created an educational mobile game aimed at children from 9 to 12 years old based on AR and tangible objects, containing a unique storyline. We then explored its utilization not only in promoting a positive attitude towards the area of chemistry, but also in the transmission of knowledge and awareness for the climate change problematic.

Our results reinforce the positive effects of using narrated games, as well as AR technologies and tangible interfaces in promoting children's motivation, knowledge and, particularly in storytelling, awareness.

We also notice that, instead of creating a game starting with the focus on the learning concepts and then adding elements that present potential to motivate the users, the key is actually to create a game that the target users would like to play just for fun and include

the learning concepts in that game, making sure that they make sense in the gameplay.

Since we were only able to perform tests with our target users in the final version of the game, there was some risk regarding the usability of the game. However, although some aspects of the game (described with more detail in the next section) need to be improved, in general the evaluation results were quite positive. Both the questionnaire and the participants' own reactions and comments show that they enjoyed the game, not only because it made them feel competent for learning new important concepts in such a short time, but also for the fun of the game itself. In addition, the participants also improved significantly their knowledge regarding basic chemistry concepts address in the game, whose results were independent of their previous experience with the used technologies. According to our questionnaire, the game also promoted a more positive attitude towards the chemistry field and awareness regarding the climate change problematic.

Finally, we could also notice some interest from the children's parents, who though the game was a great initiative mainly because they noticed a positive reaction by their children, and the fact that some children do not have quality internet access reinforces our decision to create a game that does not require internet connection.

6.2 Future work

In order to improve the overall game, before adding new game features it is important that necessary changes are made to solve some issues found in the final testing phase:

- Make some actions more obvious in the tutorial, such as the process of creating a resource. Regarding the "go to lab" button, the current icon may not be the best to represent the lab, so we can exchange it for a more obvious one, like a Periodic Table icon. Particularly during the creation of a resource, other improvements can be made such as adding a button in the spell book for each spell that shows in the cauldron the needed atoms and objects to create the resource.

- Adapt the controls to improve the player movement, or even think about an easier interaction - instead of using the current controls, show a top-view of the environment and allow the players to click directly in the items instead of having to move the player to get close to them to perform the action.

- After splitting a GHG molecule, show a panel that illustrates the atoms that form the split molecule, giving the possibility to store all the atoms at once instead of collecting them one by one.

- Readjust the time and the star score system, which currently is a bit hard for the players

Besides these referred changes, other game features could be added to improve the overall game:

- New game levels containing new stories, chemical elements, GHGs, resources (molecules and macromolecules) and climate change related information
- More character options to represent the player and allow their customization
- Present new characters of various races and ethnicities in the game levels, each one with a different role, personality and consequently with unique stories.
- Add a "save picture" button in the AR closet so that players can take pictures with the *Magic Elements* game face filters.
- Introduce a new game mode outside the game levels environment (that will become the story game mode) with a quiz containing closed-questions that convey the concepts addressed in the completed game levels working as a review of them. For each correct answer, the player will receive a certain number of coins, that he can use afterwards to "buy" new clothes for his character, new accessories (upgrade the wand and glasses, for example), new furniture to decorate the lab or new face filters in the AR closet activity. Basically, this new game mode aims to not only increase the educational effectiveness of the game but also motivate the users even more by giving them customization options, contributing to the user control, one of the game elements that promotes motivation [43].
- Allow the player to interact more with the dialogue when talking to other characters, by choosing an answer of a set of pre-made answers that also lead to new responses from the other characters, depending on the answer given by the player.
- Use cutscenes to narrate parts of the story (working like a video) instead of always using the dialogue system. We notice during the tests sessions that some players passed some stories ahead and didn't paid to much attention to it, so the cutscenes might be a solution for capturing attention in some stories. This new feature also contributes to the diversity of the game.
- Explore other physical objects and create other TUIs to enrich even more the AR immersive experience - it will be very interesting to have an AR game mode where the players could scan everyday objects that would be detected by the game using complex recognition algorithms to get the object information in terms of molecule constitution and other chemical information. Again, the players could play the game everywhere since they won't need to carry specific physical objects hard to move around, and instead they could explore many different objects and their chemical constitution.
- In the less near future, the game can also convey more advanced chemistry concepts aimed for other target groups. This idea came from one of the observations given by the interviewed chemistry teacher, who pointed out more than one time that we could expand the game to other school levels.

Although these points have potential to improve the game, more tests will need to be performed in order to re-evaluate our three main goals (attitude change regarding the chemistry field, acquired knowledge and behaviour regarding the climate change problematic). We also would like to perform tests where users play the game during a certain period of time and check if it influences the results, particularly the acquired knowledge. It could also be interesting to evaluate the game from the perspective of complementing chemistry school subjects.

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Appendix A

Physical objects - Cards

This appendix presents the illustration of the physical objects (cards) used in the Magic Elements game, starting with the cards that correspond to the atoms of the elements (oxygen and hydrogen) and ending with the subatomic particles (proton, electron and neutron).

Figure A.1: Oxygen card

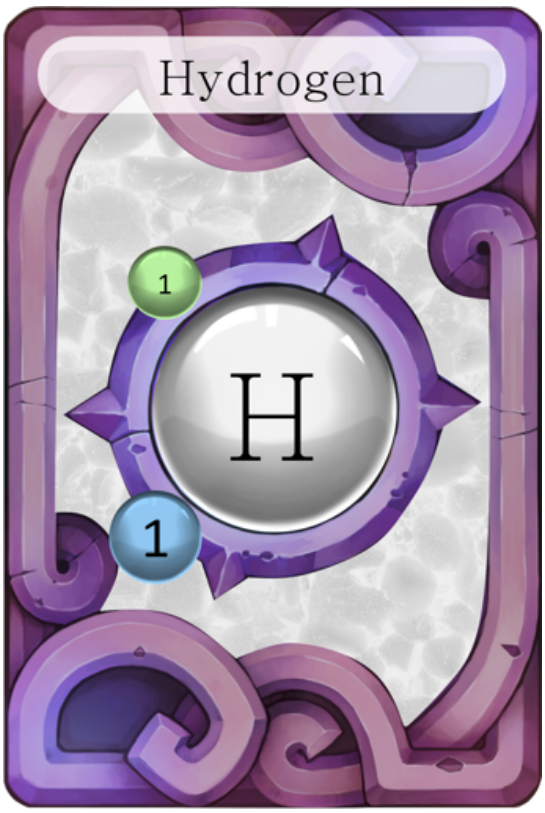

Figure A.2: Hydrogen card

Figure A.3: Proton card

Figure A.4: Electron card

Figure A.5: Neutron card

Appendix B

Questionnaire

This appendix contains the questionnaire used to carry out the assessment in the context of users. We used Google Forms, which allowed us to divide the questionnaire in sections. The first section (unnumbered) only presents a short introductory text.

Section 4 is only available to be answered for participants who answered question 1 of section 3 with a "yes" or "sometimes".

Magic Elements

Welcome to the test of the Magic Elements game!
Answer this questionnaire sincerely, as there are no right or wrong answers!
Above all - have fun!

Next

Magic Elements

*Required

S2) Identity

1) Age *

- 9
- 10
- 11
- 12
- Other: _____

2) Gender *

- Female
- Male
- Other: _____

3) School grade *

- ○ 3rd grade
- ○ 4th grade
- ○ 5th grade
- ○ 6th grade
- ○ 7th grade
- ○ Other: _____

Back Next

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Google Forms

Magic Elements

*Required

S3) Technologies experience

1) Do you usually use a mobile phone / tablet? *

- ◯ Yes
- ◯ No
- ◯ Sometimes

2) Which of the following do you usually play the most? *

- ☐ mobile phone
- ☐ tablet
- ☐ computer/pc
- ☐ I don't usually play

3) Do you have internet access at home? *

- ◯ Yes
- ◯ Yes, but with poor quality (often goes down)

- ◯ Yes, but there is a lot of lag when I play
- ◯ No
- ◯ Other: _____

4) Have you ever tried augmented reality apps? For example, instagram/facebook/ snapchat filters, Pokémon Go,... *

- ☐ Yes, I've tried instagram filters
- ☐ Yes, I've already played Pokemón Go
- ☐ Yes, I have tried other augmented reality app(s)
- ☐ No, I have never tried either

5) If you have already used another augmented reality app, say its name(s)

Your answer

Back Next

Magic Elements

*Required

S4) Mobile phone/tablet user

1) How often do you usually play on the phone/tablet? *

- ○ every day
- ○ a few days a week
- ○ a few days a month
- ○ rarely
- ○ never

2) Complete the following sentence: I usually use a mobile phone / tablet that belongs... *

- ☐ to me
- ☐ to my parents
- ☐ to my friends
- ☐ to my family
- ☐ Other: _____

3) Complete the following sentence: The mobile phone / tablet I use is ... *

- ○ Android
- ○ an iPhone
- ○ I usually use both
- ○ I don't know

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Magic Elements

*Required

S5) Pretest - Chemistry

1) What do you know about chemistry? *

Your answer

2) Do you think chemistry is: *

	1	2	3	4	5	
Very difficult	○	○	○	○	○	Very easy

3) Do you know what atoms and molecules are? *

- ○ Yes
- ○ No
- ○ I've heard of them but I don't know what they are

Back Next

Magic Elements

*Required

S6) Pretest - Chemistry (Part 1)

1) Say what you know of the following statements: (if you don't know, answer "I don't know / I don't remember") *

	True	False	I don't know/ I don't remember
Molecules contain atoms	○	○	○
Molecules do not exist	○	○	○
Greenhouse gases (GHGs) are made up of molecules	○	○	○
Atoms are very big	○	○	○
Greenhouse gases contribute to Climate change	○	○	○

2) Which of these are greenhouse gases? *

- ○ CH4 and CO2
- ○ CH2 and CO

- ◯ I don't know/ I don't remember

3) Select the atoms you know: *

- ☐ H (Hydrogen)
- ☐ N (Nitro)
- ☐ H (Hydro)
- ☐ O (Oxygen)
- ☐ C (Coal)
- ☐ C (Carbon)
- ☐ I don't know/ I don't remember

4) Atoms are made up of: (You can answer to more than one) *

- ☐ Protons
- ☐ Dotrons
- ☐ Leutrons
- ☐ Electrons
- ☐ Neutrons
- ☐ I don't know/ I don't remember

5) What is the chemical formula of water? *

- ◯ H2O (H + H + O)
- ◯ HO (H + O)
- ◯ HO2 (H + O + O)

- ◯ I don't know/ I don't remember

6) What is the chemical formula of dioxygen? *

- ◯ 02 (0 + 0)
- ◯ 0
- ◯ H0 (H + 0)
- ◯ I don't know/ I don't remember

7) The diamond is a... *

- ◯ macromolecule, consisting of Carbons (C)
- ◯ molecule, consisting of Carbons (C)
- ◯ I don't know/ I don't remember

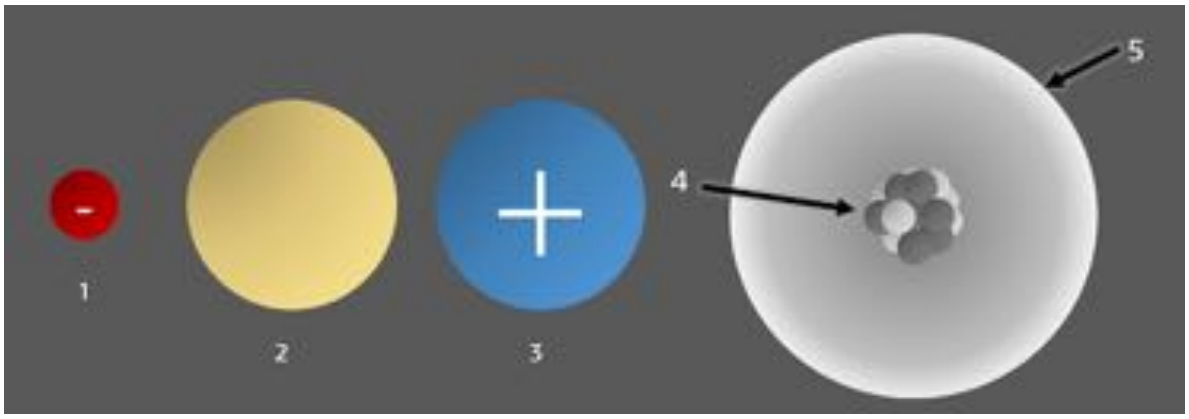
Back Next

Magic Elements

*Required

S7) Pretest - Chemistry (Part 2)

1) Caption the following images: *

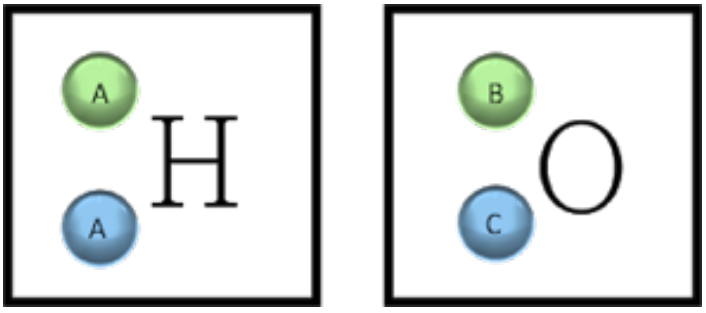


	Nucleus	Electronic cloud	Proton	Electron	Neutron	I don't know/ I don't remember
1	○	○	○	○	○	○
2	○	○	○	○	○	○
3	○	○	○	○	○	○
4	○	○	○	○	○	○
5	○	○	○	○	○	○

2) Where can we find each of the following particles? *

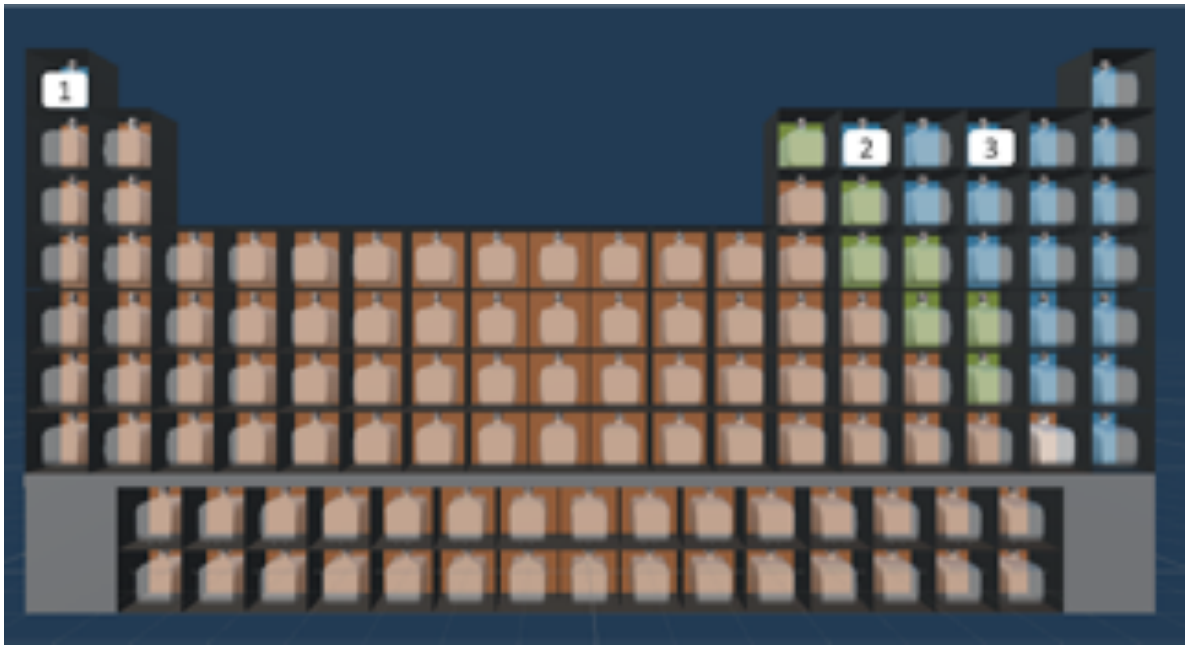
	Nucleus	Electronic cloud	I don't know/ I don't remember
Electron	○	○	○
Proton	○	○	○
Neutron	○	○	○

3) What numbers are hidden behind the letters? *



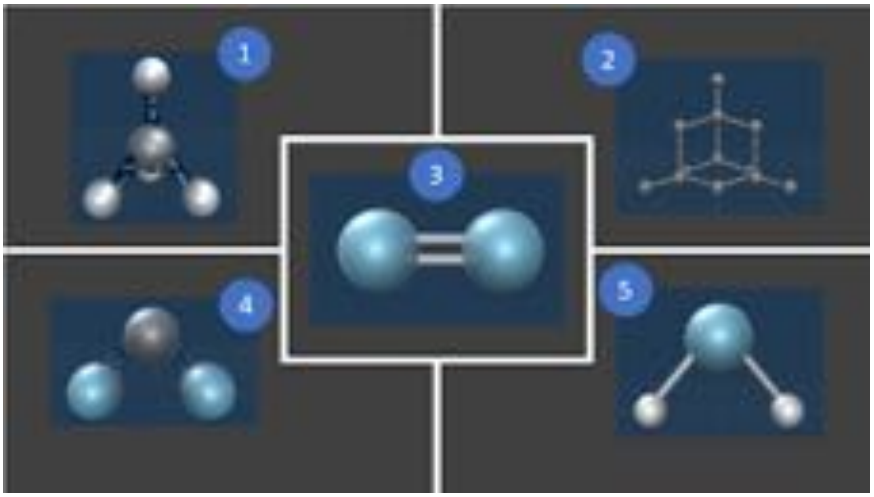
	1	16	8	I don't know/ I don't remember
A	○	○	○	○
B	○	○	○	○
C	○	○	○	○

4) Which elements are in the following positions of the Periodic Table: *



	C (Carbon)	H (Hydrogen)	O (Oxygen)	I don't know/ I don't remember
1	○	○	○	○
2	○	○	○	○
3	○	○	○	○

5) The models belong to: *



	water molecule	dioxygen	carbon dioxide	methane	diamond	I don't know/ I don't remember
1	○	○	○	○	○	○
2	○	○	○	○	○	○
3	○	○	○	○	○	○
4	○	○	○	○	○	○
5	○	○	○	○	○	○

Back Next

Magic Elements

*Required

S8) Pretest - Climate change

1) Say in your own words what climate change is (answer I don't know/ I don't remember if that's the case) *

Your answer

2) What can you do on Earth to soften the impacts of climate change? *

- [ ] Play more on the computer
- [ ] Turn off appliances, light and water when I'm not using them
- [ ] Buying more stuff and spending more money
- [ ] Recycling
- [ ] Reusing
- [ ] I don't know / I don't remember

3) How important do you think it is to fight climate change? *

	1	2	3	4	5	
Somewhat important	○	○	○	○	○	Very important

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Magic Elements

Test/Play the game

Go to the next section only after you finish playing the game

Image By Silsor - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=395316

Back Next

Magic Elements

*Required

S10) Motivation

1) The game has an attractive design (world of magic, animations, characters, enchanted objects) *

	1	2	3	4	5	
It's ok	○	○	○	○	○	Yes, very attractive!

2) Do you remember what was the goal of the game? (You can choose multiple answers) *

- [ ] Yes, I had to find a way out before time ran out
- [ ] Yes, I had to create water, oxygen and diamond
- [ ] Yes, I had to be the best wizard of all
- [ ] Yes, I had to destroy Lemuria
- [ ] I don't know/ I don't remember

3) Did you struggle to move the character? *

- Yes
- No
- A little

4) Did you get lost and wondered what to do (for a while)? *

- Yes, once
- Yes, twice
- Yes, three or more times
- No

5) If you answered yes to the previous answer, say when it happened, or answer "I don't know / I don't remember"

Your answer

6) Do you think the game is useful and important? *

	1	2	3	4	5	
A little	○	○	○	○	○	Yes, a lot!

7) Why? *

Your answer

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Google Forms

Magic Elements

*Required

S11) Experience

1) Throughout the game I felt like continuing to play and winning the game *

	1	2	3	4	5	
A little	○	○	○	○	○	Yes, a lot!

2) Did you win the game? *

- ○ Yes, on the first try
- ○ Yes, on the second try
- ○ Yes, on the third or highest attempt

3) Evaluate how much fun you thought the game was: *

	1	2	3	4	5	
It's ok	○	○	○	○	○	It was so much fun!

4) Would you like the game to have more levels to keep playing it longer? *

- ○ Yes
- ○ No
- ○ Maybe

5) Would you like to play this game again? *

- ○ Yes, because it is a fun game to learn chemistry
- ○ Maybe
- ○ No
- ○ Other: _____

6) After playing this game, I think chemistry is: *

	1	2	3	4	5	
Very difficult	○	○	○	○	○	Very easy

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Magic Elements

*Required

S12) Technologies influence

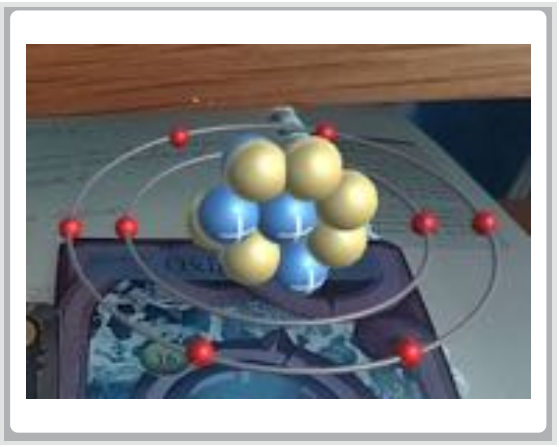
1) Sort the activities: (1- liked the most, 4-liked it less) *

	1 - Better	2	3	4 - Worse
Stories	○	○	○	○
AR face filters	○	○	○	○
AR activity to build an atom using cards	○	○	○	○
AR molecule visualizer	○	○	○	○

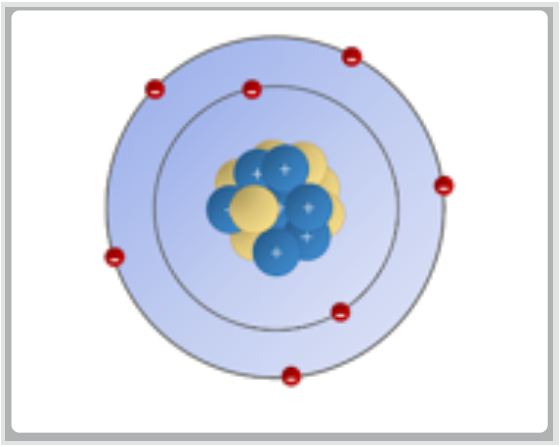
2) In which of the augmented reality activities did you get to see 3D objects better? *

- ○ Building atoms using cards
- ○ See molecules without cards

3) Do you think it's easier to understand atoms and molecules ... *



in 3D using augmented reality



on a paper image

4) Would you like to repeat the levels where you still don't have 3 stars to improve your score? *

	1	2	3	4	5	
Maybe	○	○	○	○	○	Yes, a lot!

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Google Forms

Magic Elements

*Required

S13) Acquired knowledge (Part 1)

1) Say what you know of the following statements: (if you don't know, answer "I don't know / I don't remember") *

	True	False	I don't know/ I don't remember
Molecules contain atoms	○	○	○
Molecules do not exist	○	○	○
Greenhouse gases (GHGs) are made up of molecules	○	○	○
Atoms are very big	○	○	○
Greenhouse gases contribute to Climate change	○	○	○

2) Which of these are greenhouse gases? *

○ CH4 and CO2

- ◯ CH2 and CO
- ◯ I don't know/ I don't remember

3) Select the atoms you found in the game: *

- ☐ H (Hydrogen)
- ☐ N (Nitro)
- ☐ H (Hydro)
- ☐ O (Oxygen)
- ☐ C (Coal)
- ☐ C (Carbon)
- ☐ I don't know/ I don't remember

4) Atoms are made up of: (You can answer to more than one) *

- ☐ Protons
- ☐ Dotrons
- ☐ Leutrons
- ☐ Electrons
- ☐ Neutrons
- ☐ I don't know/ I don't remember

5) What is the chemical formula of water? *

- ◯ H2O (H + H + O)
- ◯ HO (H + O)

- ◯ HO2 (H + O + O)
- ◯ I don't know/ I don't remember

6) What is the chemical formula of dioxygen? *

- ◯ O2 (O + O)
- ◯ O
- ◯ HO (H + O)
- ◯ I don't know/ I don't remember

7) The diamond is a... *

- ◯ macromolecule, consisting of Carbons (C)
- ◯ molecule, consisting of Carbons (C)
- ◯ I don't know/ I don't remember

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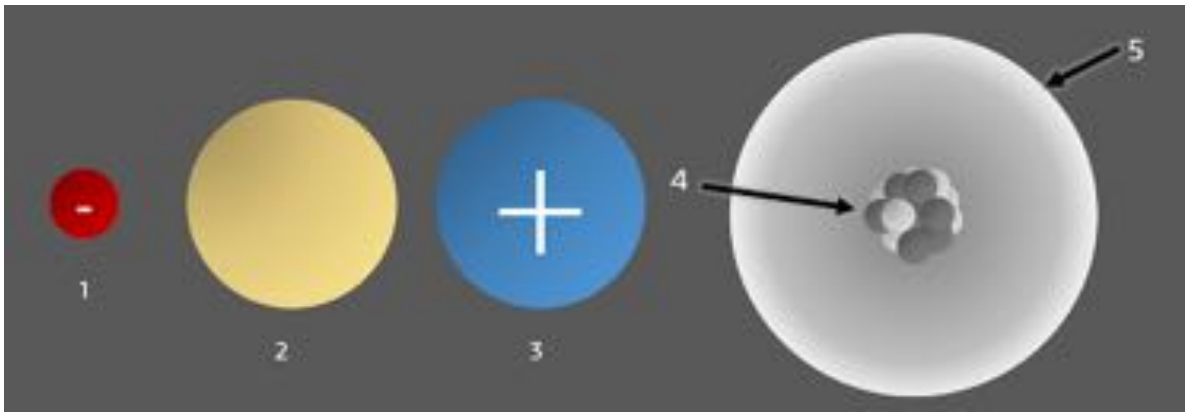
Magic Elements

*Required

S14) Acquired knowledge (Part 2)

1) Caption the following images: *



	Nucleus	Electronic cloud	Proton	Electron	Neutron	I don't know/ I don't remember
1	○	○	○	○	○	○
2	○	○	○	○	○	○
3	○	○	○	○	○	○
4	○	○	○	○	○	○
5	○	○	○	○	○	○

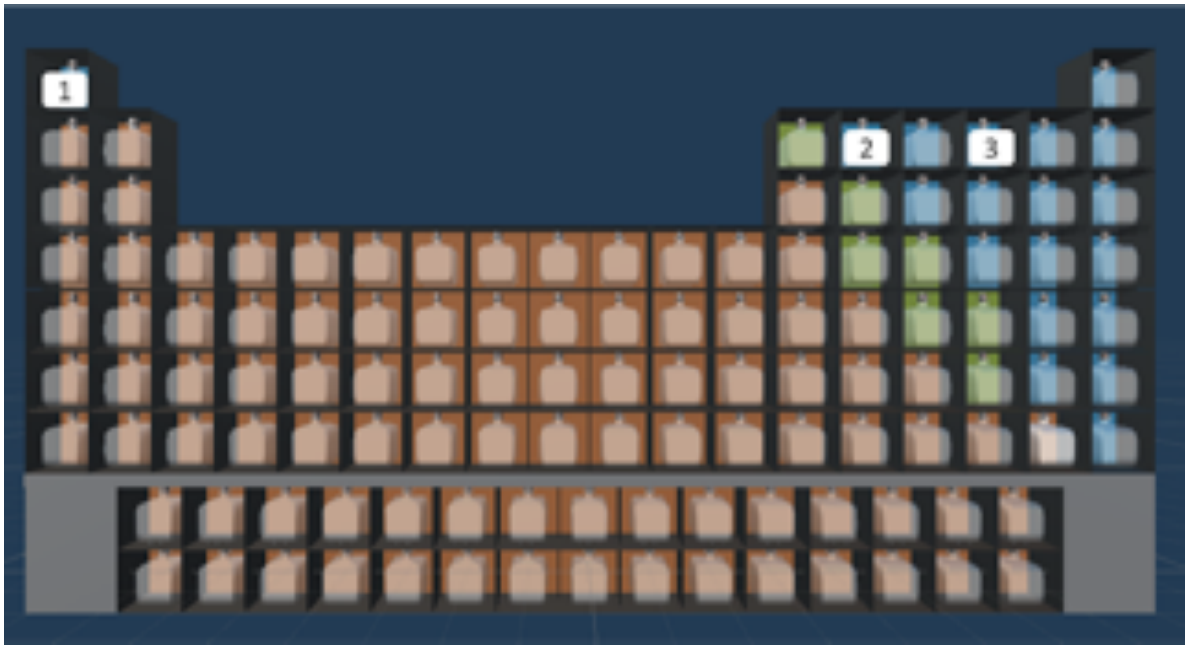
2) Where can we find each of the following particles? *

	Nucleus	Electronic cloud	I don't know/ I don't remember
Electron	○	○	○
Proton	○	○	○
Neutron	○	○	○

3) What numbers are hidden behind the letters? *

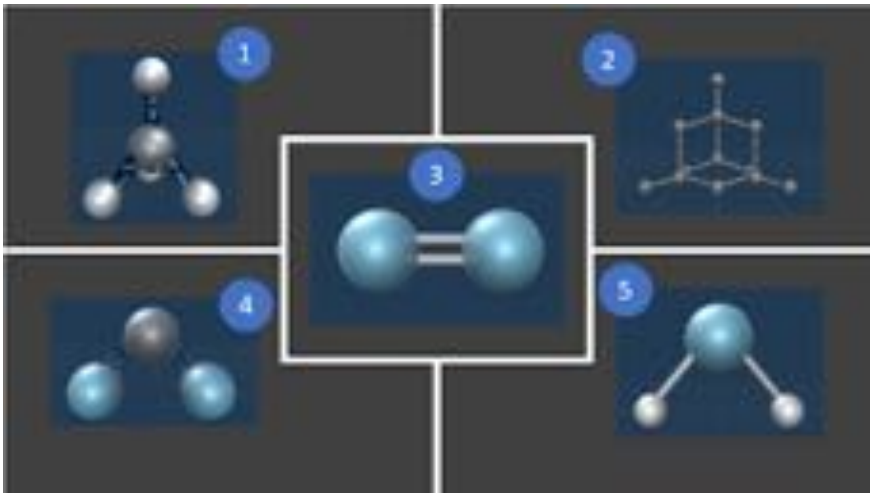
	1	8	16	I don't know/ I don't remember
A	○	○	○	○
B	○	○	○	○
C	○	○	○	○

4) Which elements are in the following positions of the Periodic Table: *



	C (Carbon)	H (Hydrogen)	O (Oxygen)	I don't know/ I don't remember
1	○	○	○	○
2	○	○	○	○
3	○	○	○	○

5) The models belong to: *



	water molecule	dioxygen	carbon dioxide	methane	diamond	I don't know/ I don't remember
1	○	○	○	○	○	○
2	○	○	○	○	○	○
3	○	○	○	○	○	○
4	○	○	○	○	○	○
5	○	○	○	○	○	○

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Magic Elements

*Required

S15) Let's change the world?

1) Both in Lemuria and on Earth, climate change is a very serious problem. Why? *

Your answer

2) What can you do on Earth to soften the impacts of climate change? *

- [ ] Play more on the computer
- [ ] Turn off appliances, light and water when I'm not using them
- [ ] Buying more stuff and spending more money
- [ ] Recycling
- [ ] Reusing
- [ ] I don't know/ I don't remember

3) How important do you think it is to fight climate change? *

1 2 3 4 5

Somewhat important ○ ○ ○ ○ ○ Very important

4) Would you like to contribute to not letting climate change attack even more and bring more bad things? *

1 2 3 4 5

Yes, I can help ○ ○ ○ ○ ○ Yes, I want to help!

5) Now that you've answered all the questions, do you want to play the game again and find out if your answers are right? *

1 2 3 4 5

A little bit ○ ○ ○ ○ ○ Yes, a lot!

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Appendix C

Questionnaire results

This appendix presents the results of the questionnaire. Questions 1 and 5 of both sections 7 and 14 are presented more clearly at the end.

Magic Elements

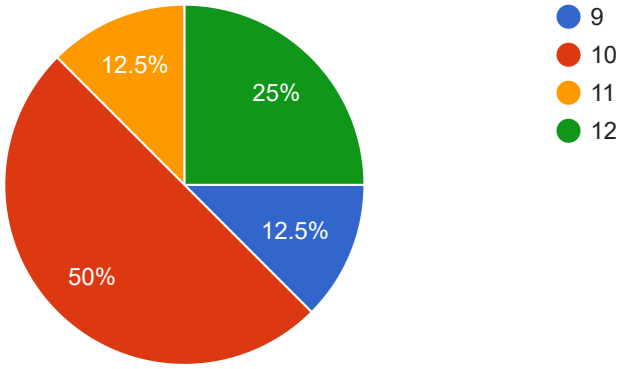
8 responses

Publish analytics

S2) Identity

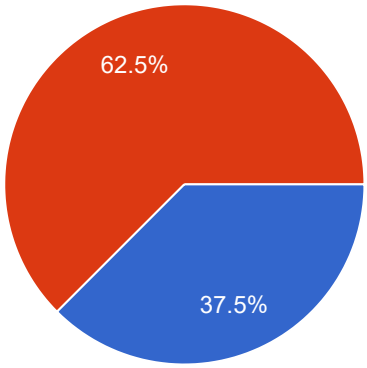
1) Age

8 responses



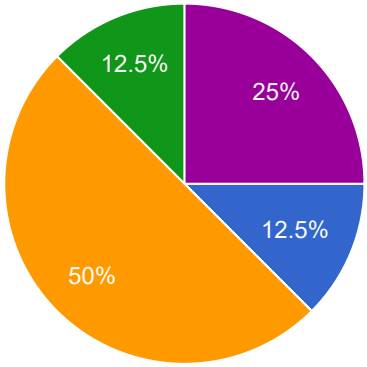
2) Gender

8 responses



3) School grade

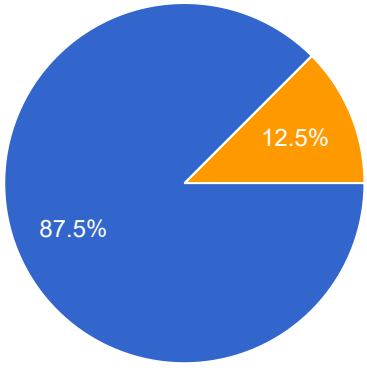
8 responses



S3) Technologies experience

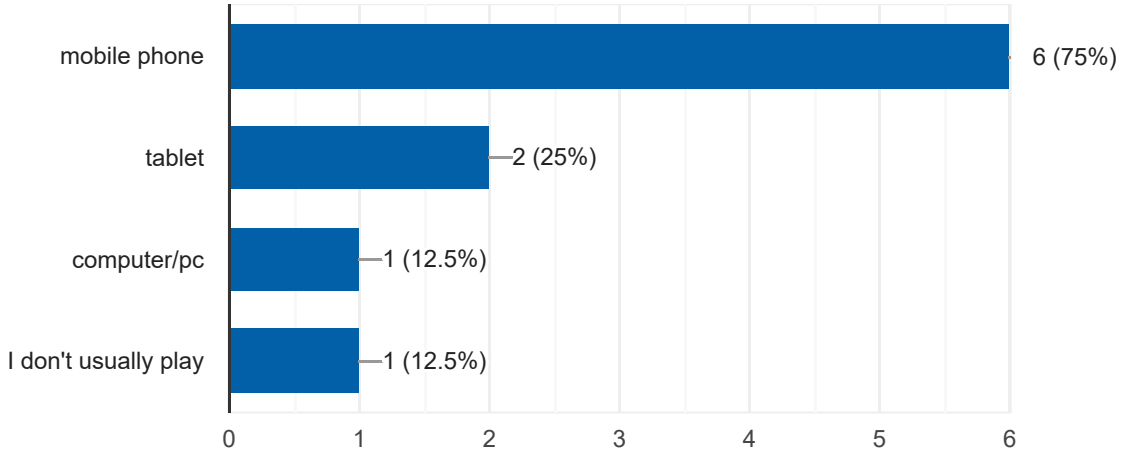
1) Do you usually use a mobile phone / tablet?

8 responses



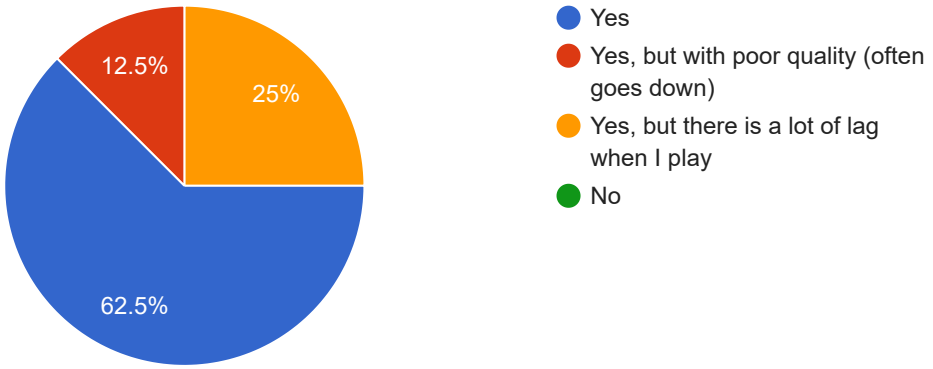
2) Which of the following do you usually play the most?

8 responses



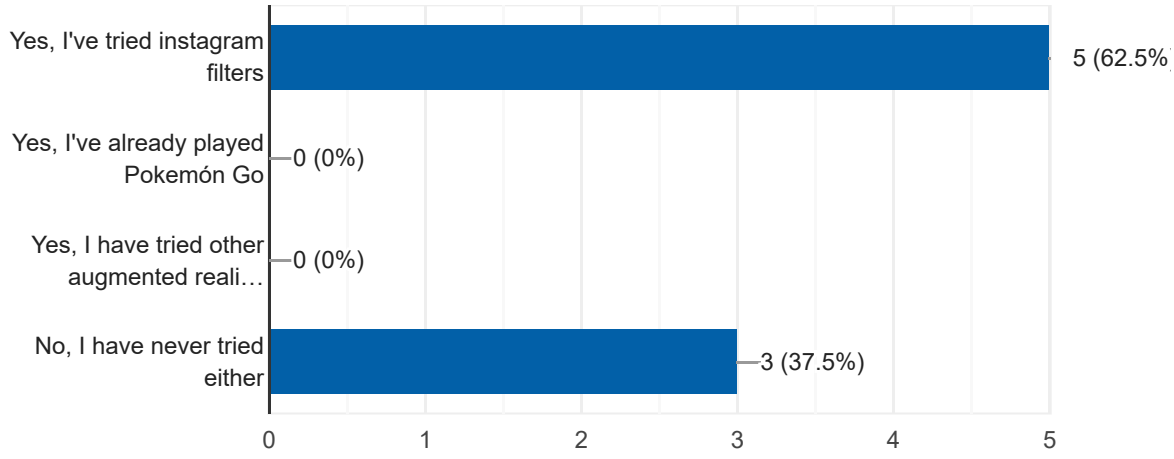
3) Do you have internet access at home?

8 responses



4) Have you ever tried augmented reality apps? For example, instagram/ facebook/ snapchat filters, Pokémon Go,...

8 responses



5) If you have already used another augmented reality app, say its name(s)

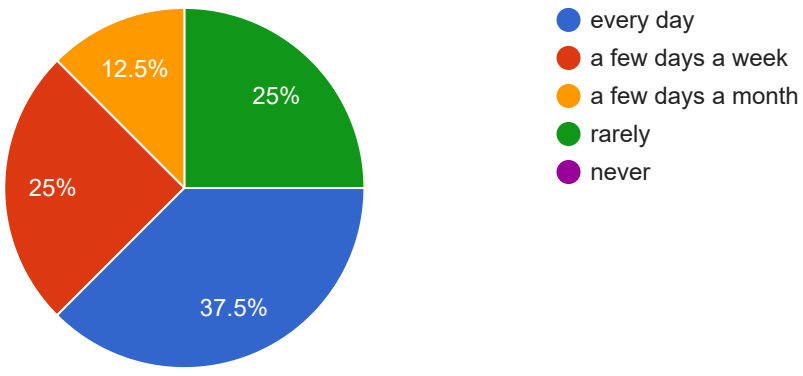
0 responses

No responses yet for this question.

S4) Mobile phone/tablet user

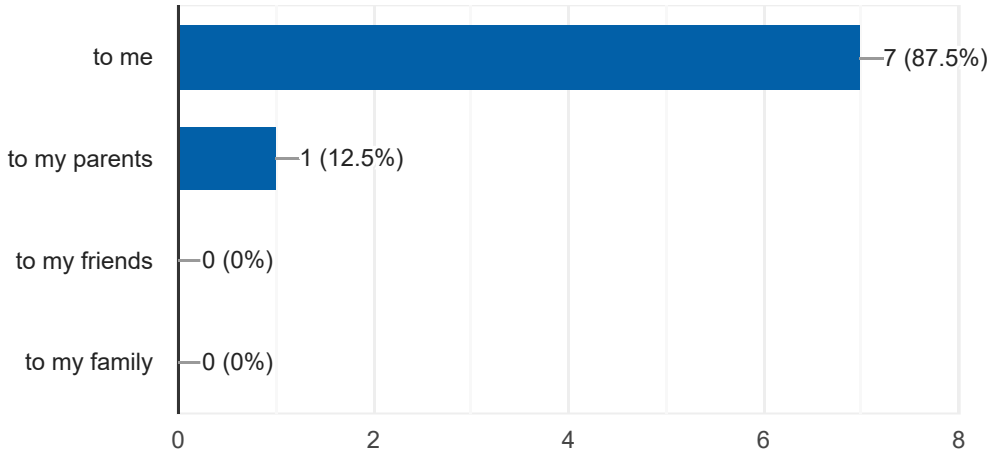
1) How often do you usually play on the phone/tablet?

8 responses



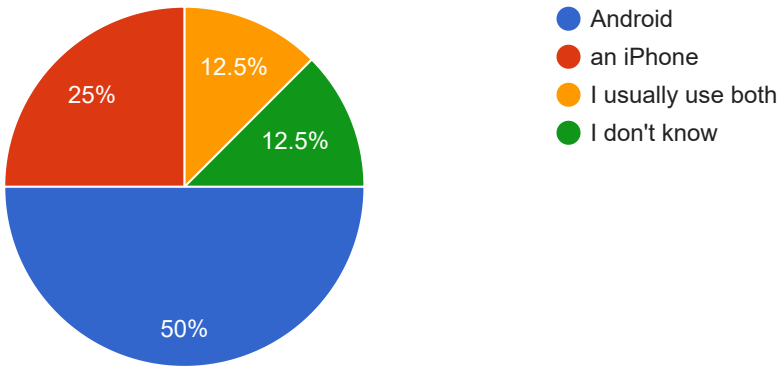
2) Complete the following sentence: I usually use a mobile phone / tablet that belongs...

8 responses



3) Complete the following sentence: The mobile phone / tablet I use is ...

8 responses



S5) Pretest - Chemistry

1) What do you know about chemistry?

8 responses

nothing

I know it is a hard school subject.

I know it is a school subject.

I've heard about it, it is a school subject

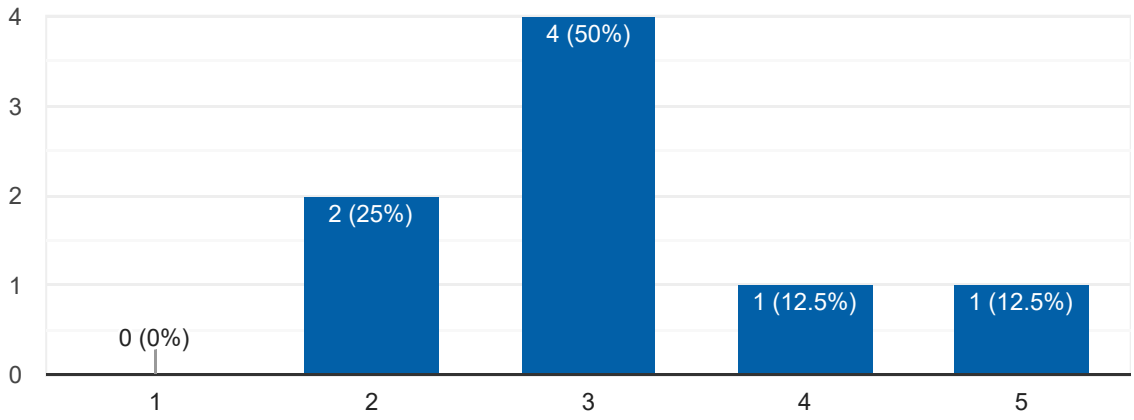
school subject, scientific, it has gases and the periodic table

school subject

school subjects where you make a lot of chemical experiences

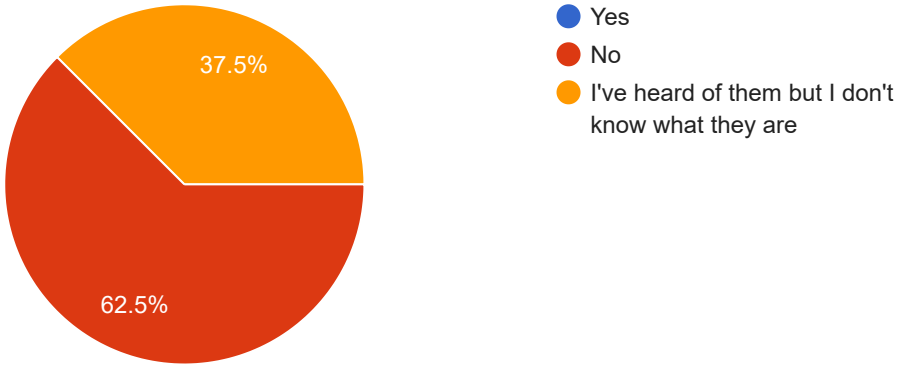
2) Do you think chemistry is:

8 responses



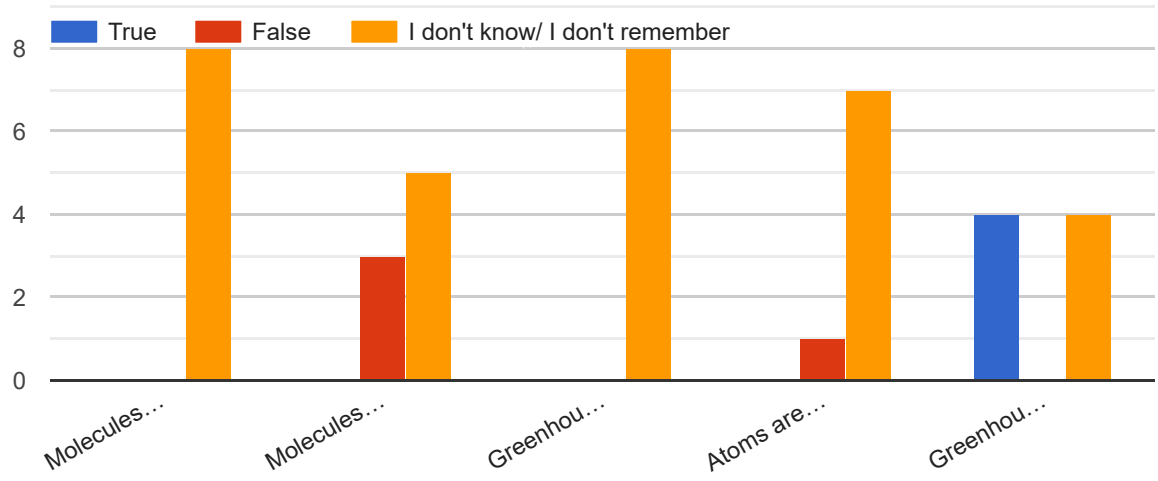
3) Do you know what atoms and molecules are?

8 responses



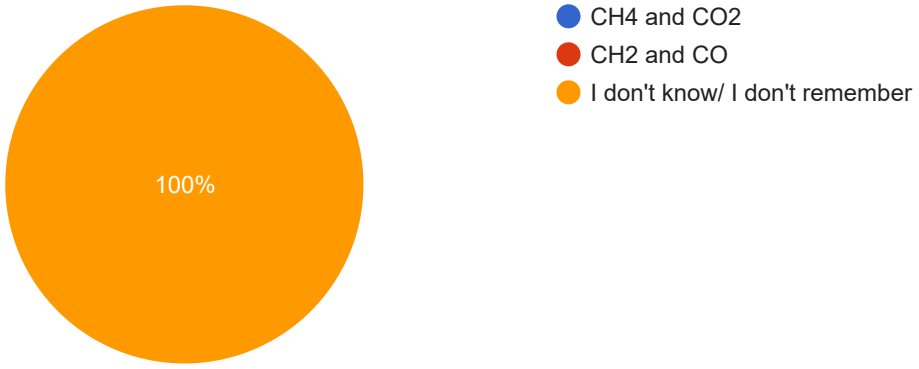
S6) Pretest - Chemistry (Part 1)

1) Say what you know of the following statements: (if you don't know, answer "I don't know / I don't remember")



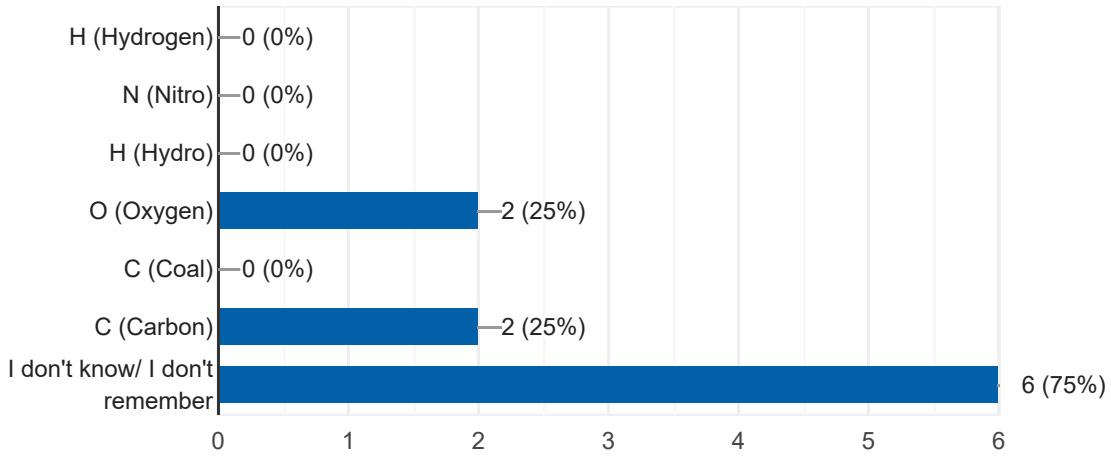
2) Which of these are greenhouse gases?

8 responses



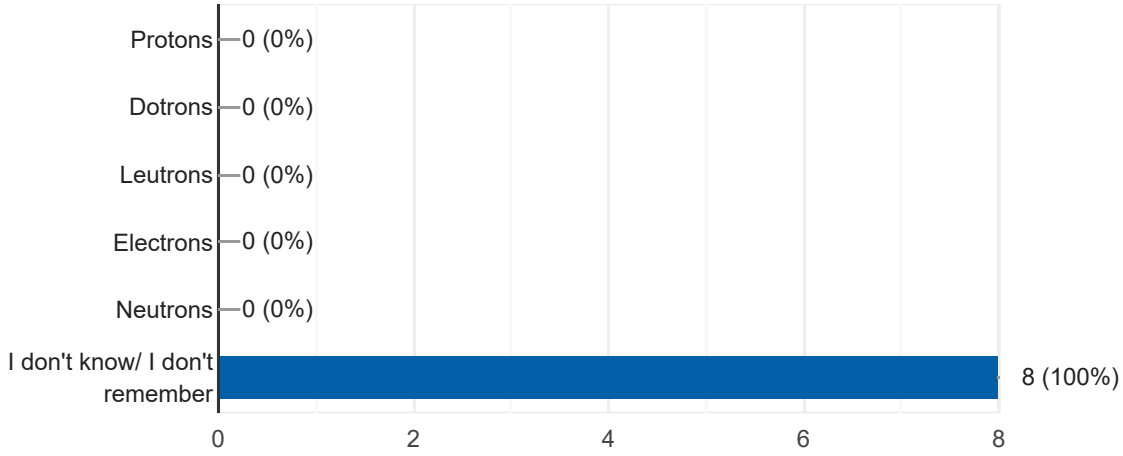
3) Select the atoms you know:

8 responses



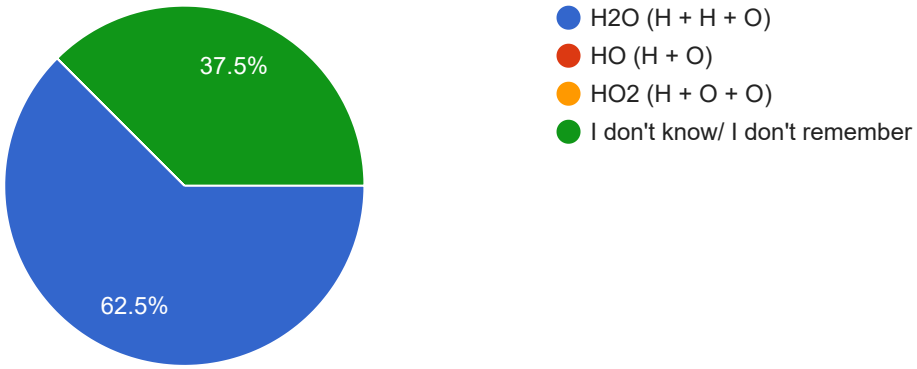
4) Atoms are made up of: (You can answer to more than one)

8 responses



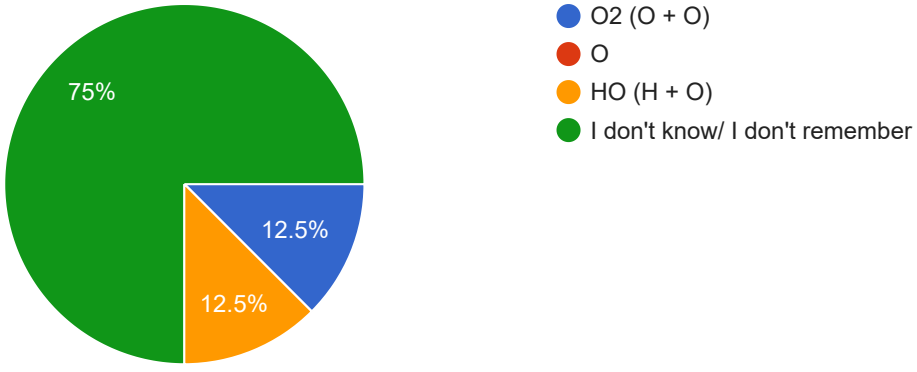
5) What is the chemical formula of water?

8 responses



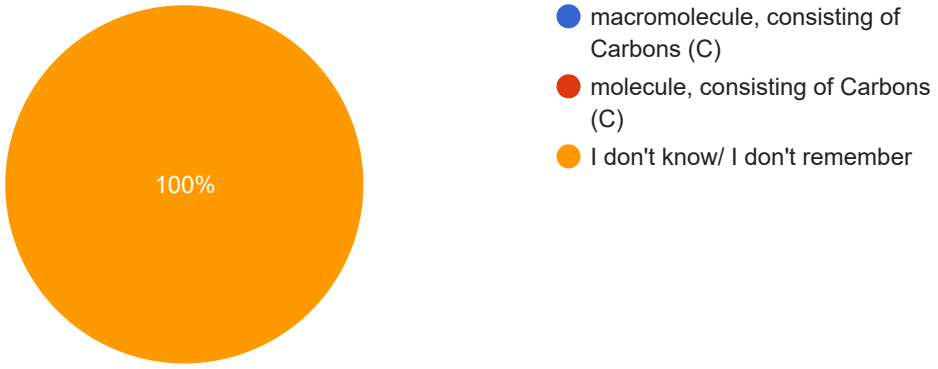
6) What is the chemical formula of dioxygen?

8 responses



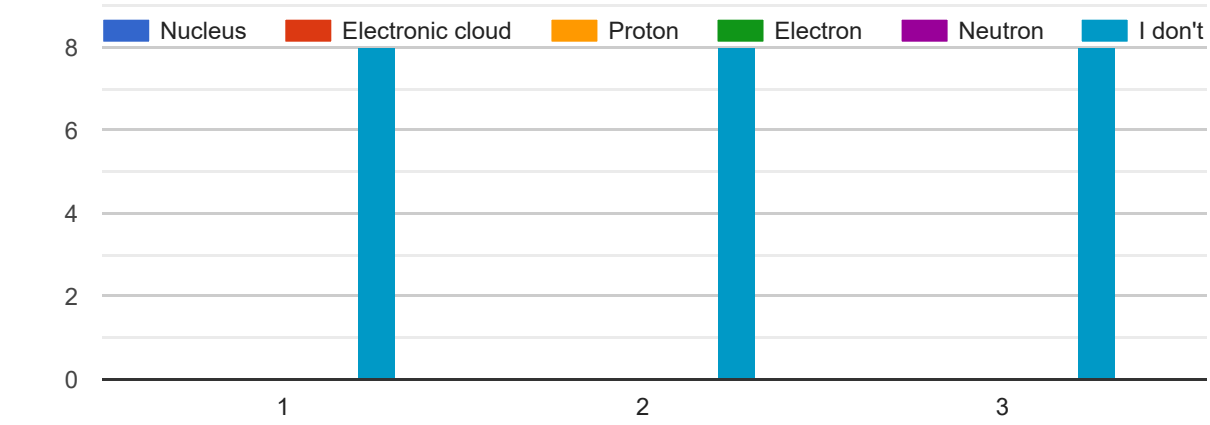
7) The diamond is a...

8 responses

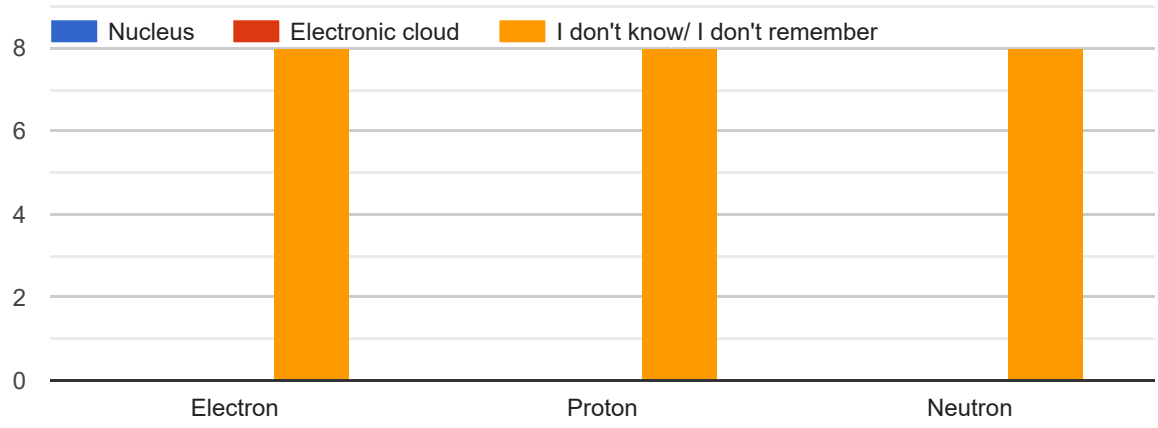


S7) Pretest - Chemistry (Part 2)

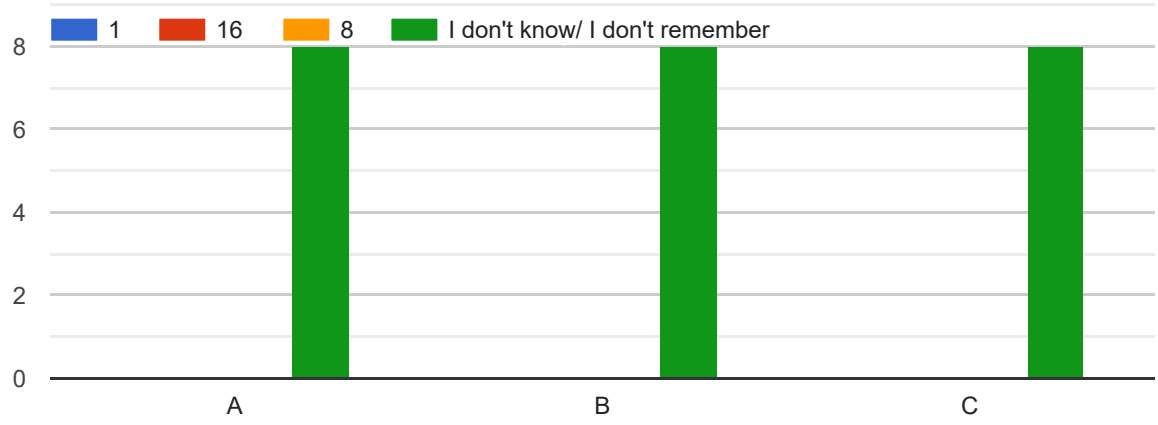
1) Caption the following images:



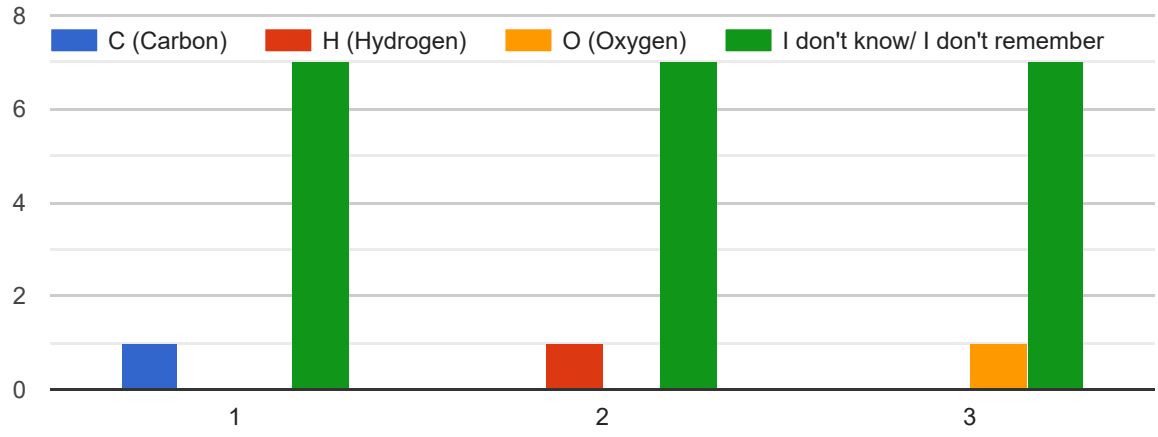
2) Where can we find each of the following particles?



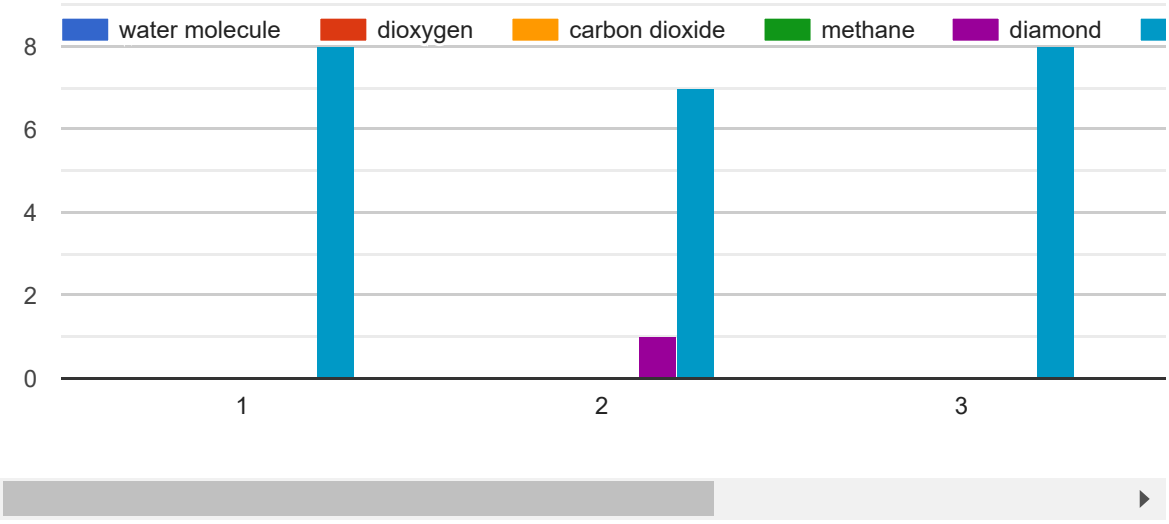
3) What numbers are hidden behind the letters?



4) Which elements are in the following positions of the Periodic Table:



5) The models belong to:



S8) Pretest - Climate change

1) Say in your own words what climate change is (answer I don't know / I don't remember if that's the case)

8 responses

I don't know

I've heard about it

Climate change is a negative thing.

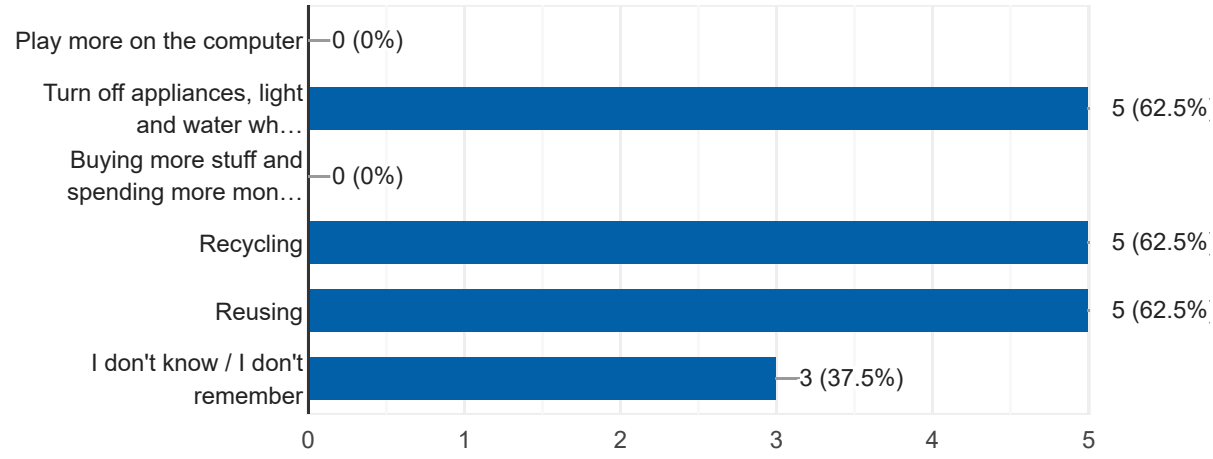
it is a bad thing

It is a bad thing

I think it is a good thing

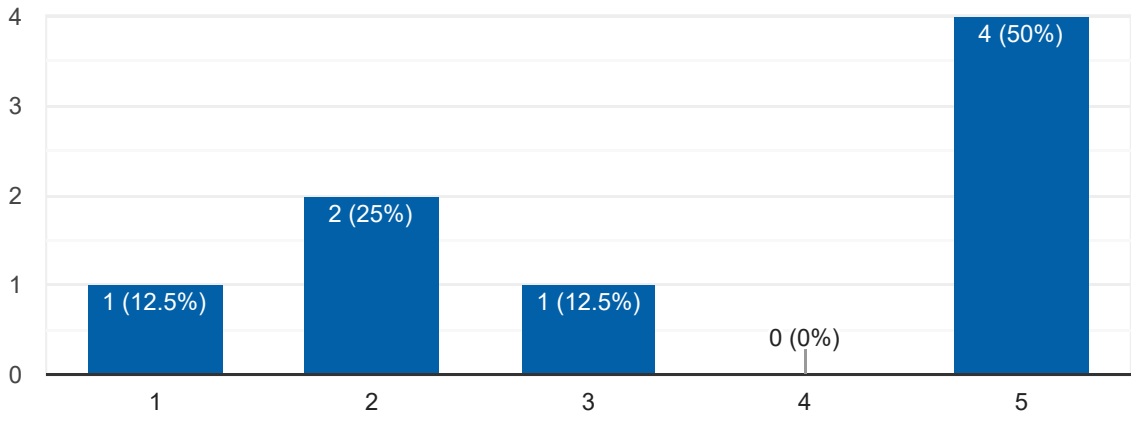
2) What can you do on Earth to soften the impacts of climate change?

8 responses



3) How important do you think it is to fight climate change?

8 responses

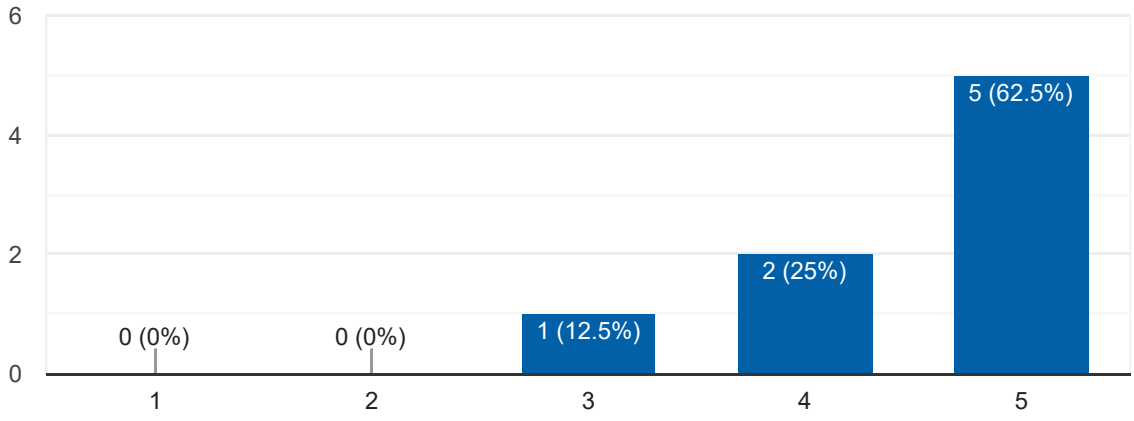


Test/Play the game

S10) Motivation

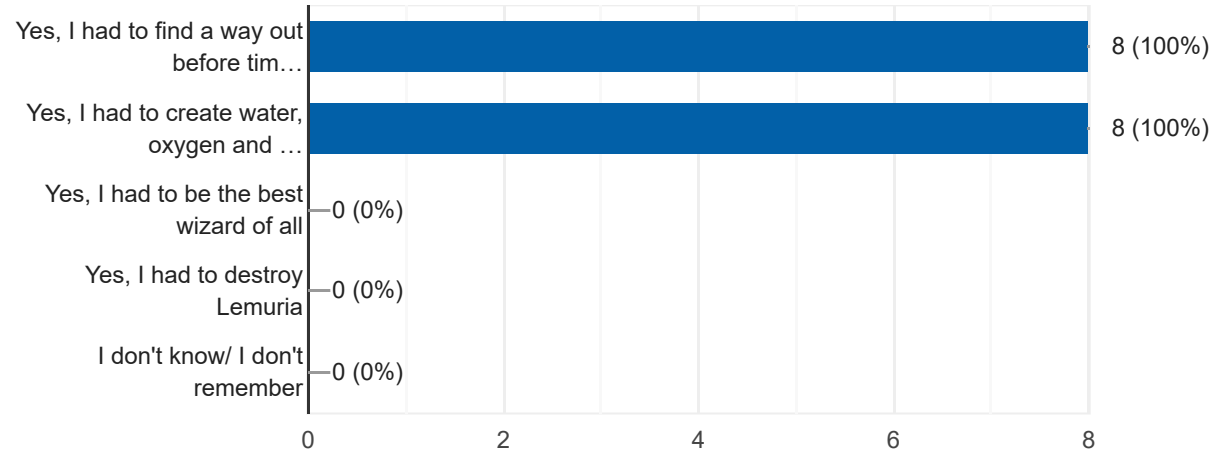
1) The game has an attractive design (world of magic, animations, characters, enchanted objects)

8 responses



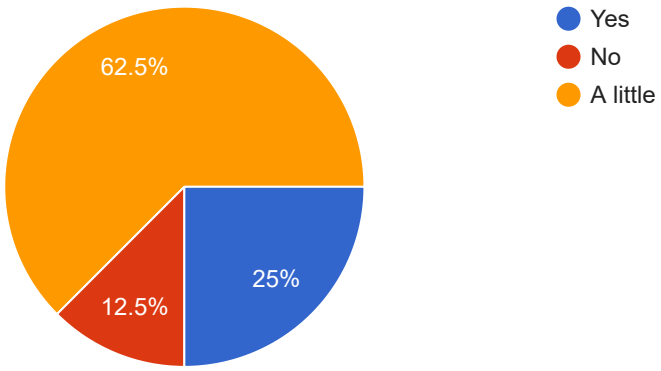
2) Do you remember what was the goal of the game? (You can choose multiple answers)

8 responses



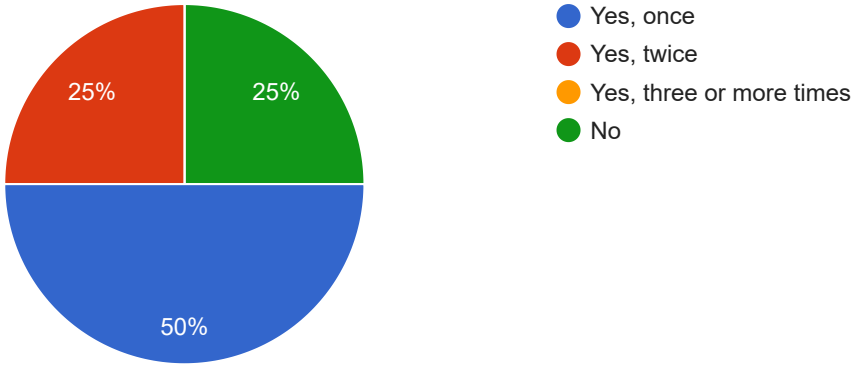
3) Did you struggle to move the character?

8 responses



4) Did you get lost and wondered what to do (for a while)?

8 responses



5) If you answered yes to the previous answer, say when it happened, or answer "I don't know/ I don't remember"

6 responses

Leave the lab.

Go to lab.

go to lab and find key

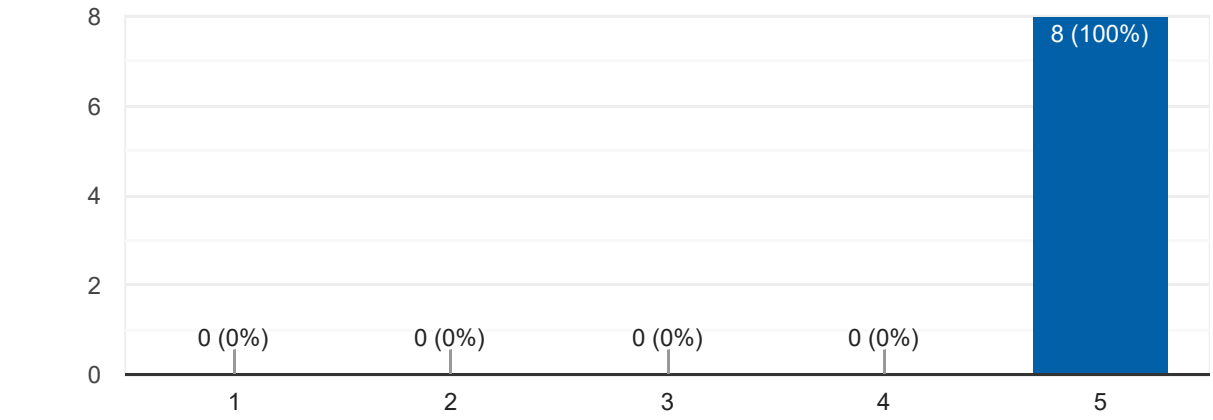
in the first level to split

Back to world and create in the lab

go to lab

6) Do you think the game is useful and important?

8 responses



7) Why?

8 responses

It has important information on how to fight climate change.

It was about how to improve climate change.

It is good to learn new things

Because we need to think so we can win the game

because it teaches chemistry and that's important

because it teaches us some things

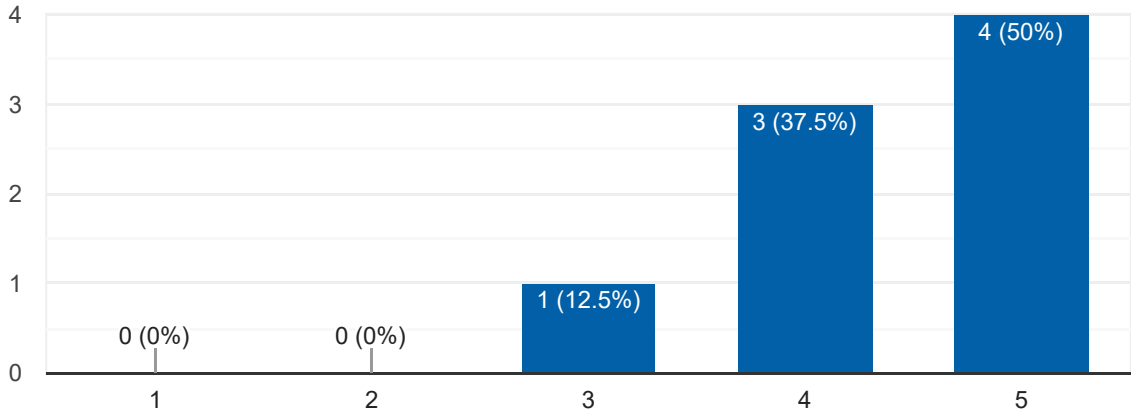
We can learn chemistry in a fun way

because we can learn

S11) Experience

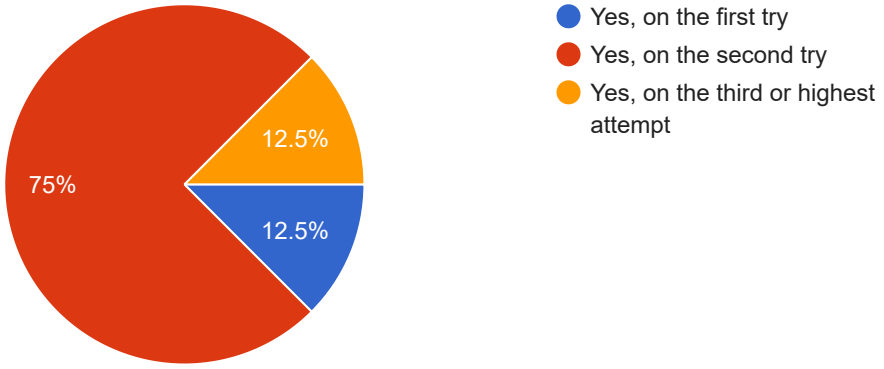
1) Throughout the game I felt like continuing to play and winning the game

8 responses



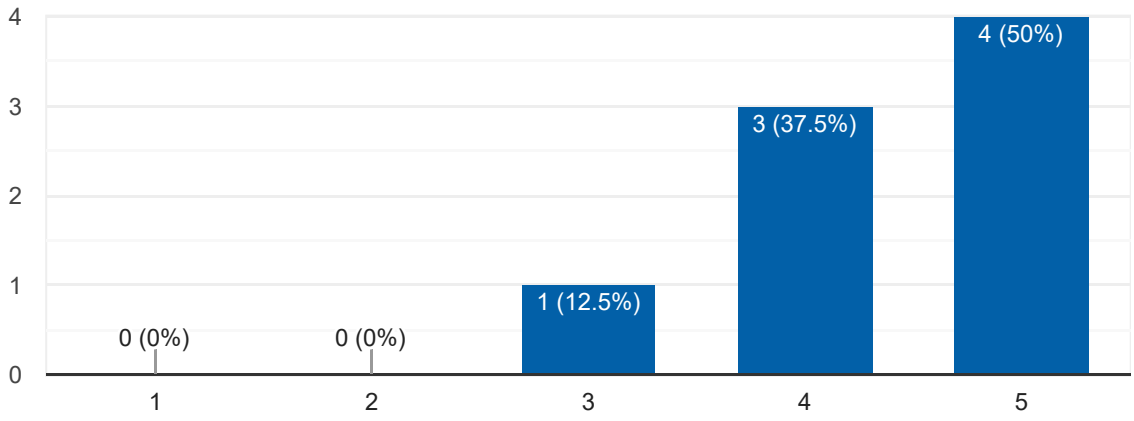
2) Did you win the game?

8 responses



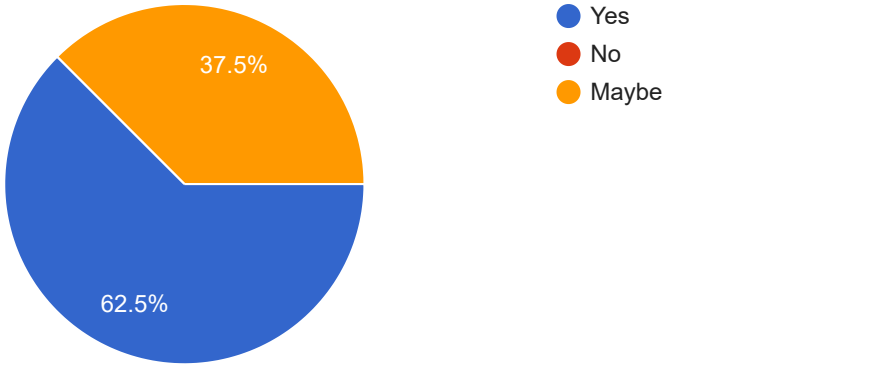
3) Evaluate how much fun you thought the game was:

8 responses



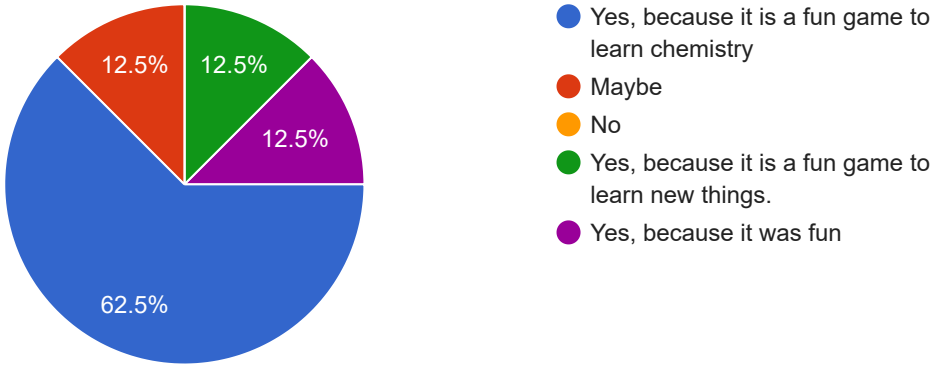
4) Would you like the game to have more levels to keep playing it longer?

8 responses



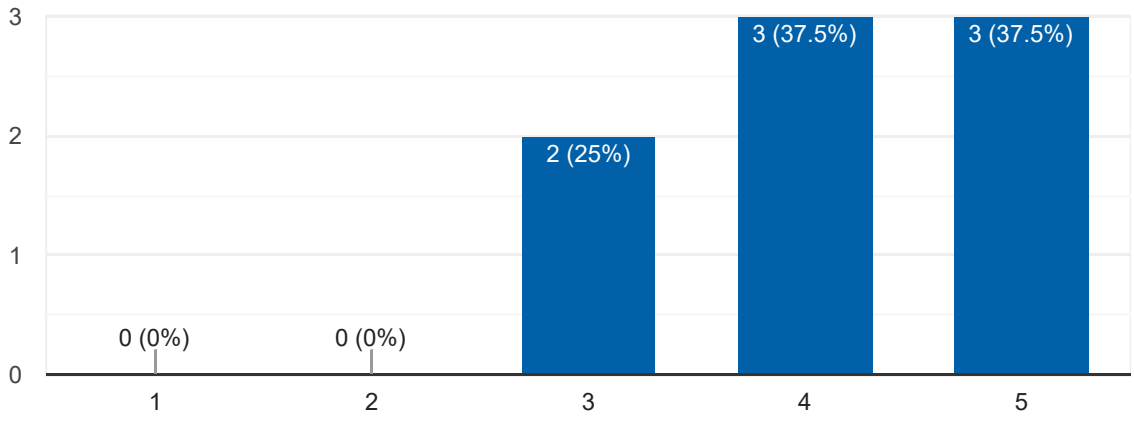
5) Would you like to play this game again?

8 responses



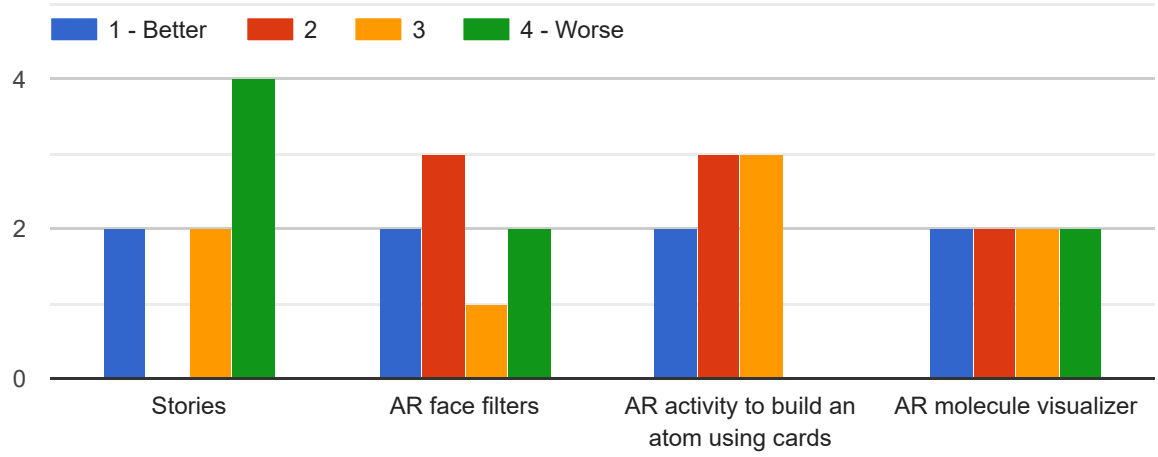
6) After playing this game, I think chemistry is:

8 responses



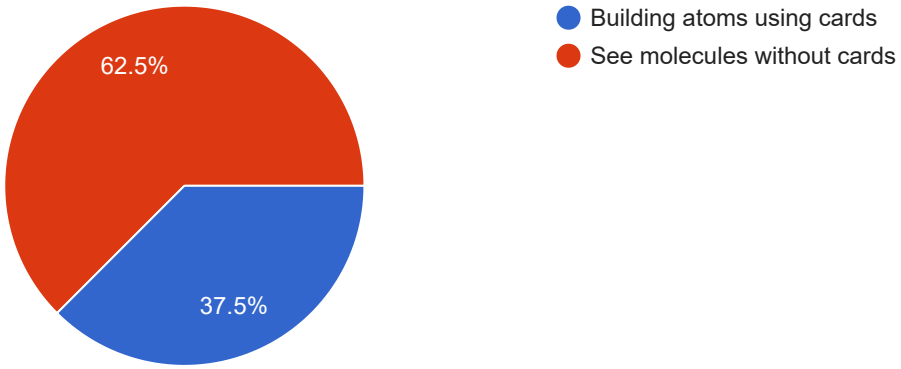
S12) Technologies influence

1) Sort the activities: (1- liked the most, 4-liked it less)



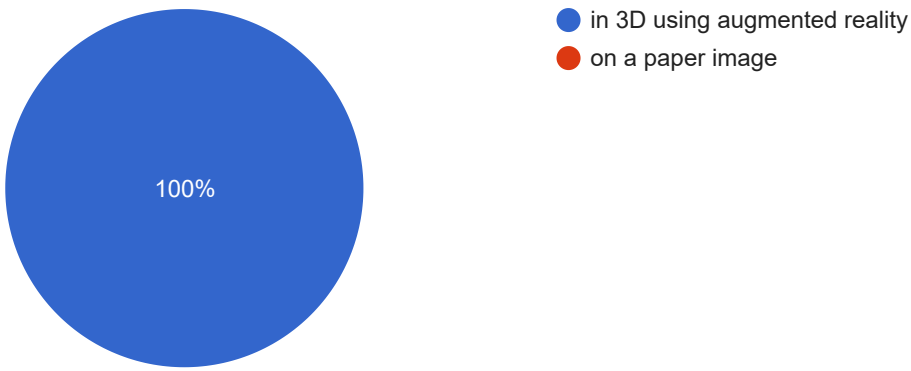
2) In which of the augmented reality activities did you get to see 3D objects better?

8 responses



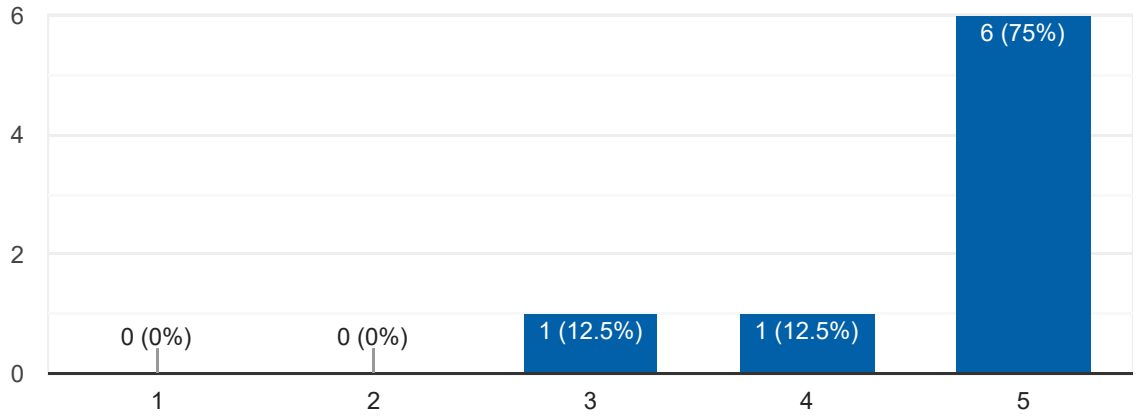
3) Do you think it's easier to understand atoms and molecules ...

8 responses



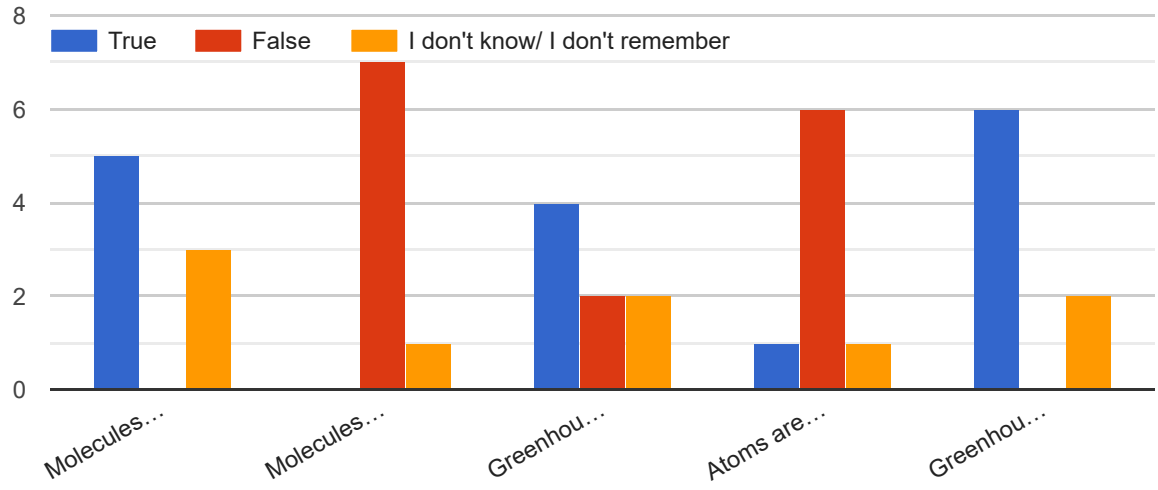
4) Would you like to repeat the levels where you still don't have 3 stars to improve your score?

8 responses



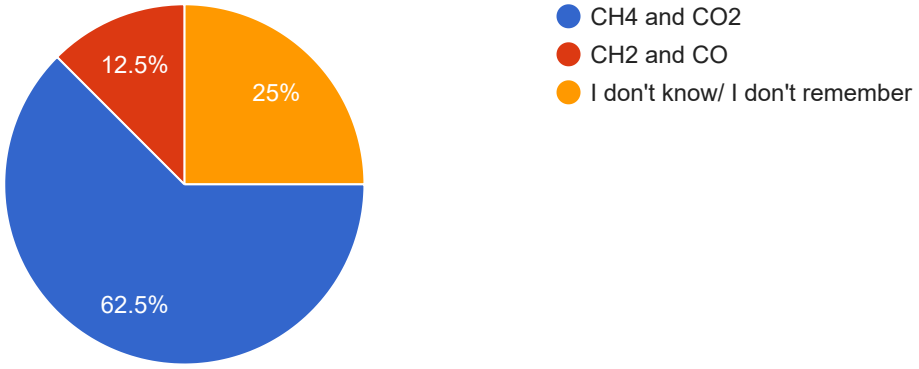
S13) Acquired knowledge (Part 1)

1) Say what you know of the following statements: (if you don't know, answer "I don't know / I don't remember")



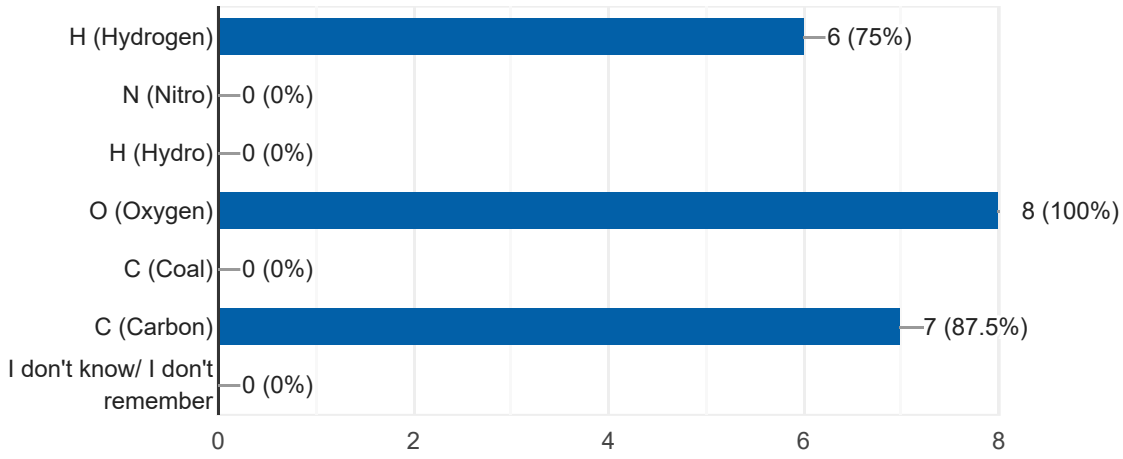
2) Which of these are greenhouse gases?

8 responses



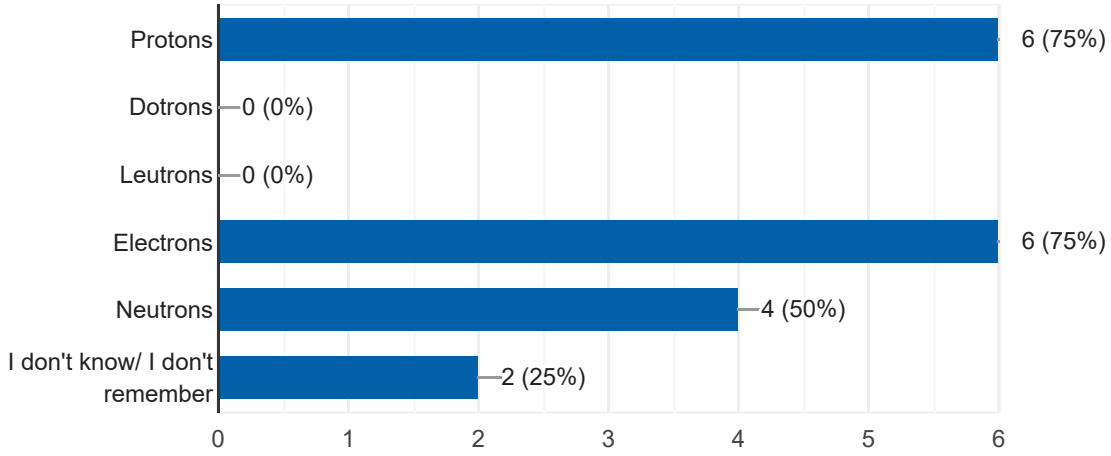
3) Select the atoms you found in the game:

8 responses



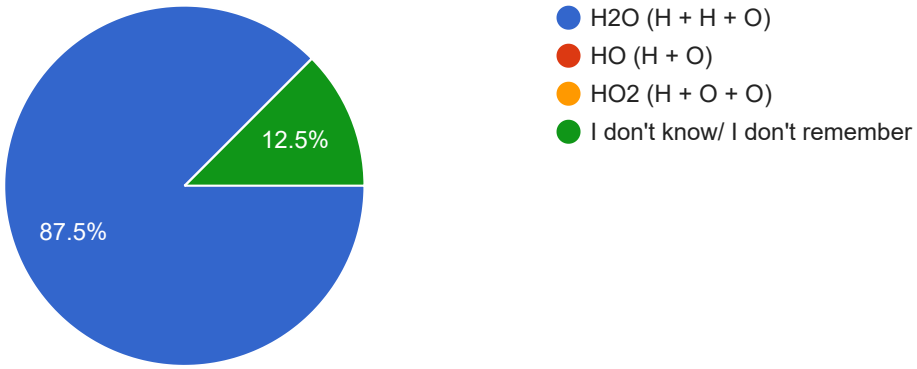
4) Atoms are made up of: (You can answer to more than one)

8 responses



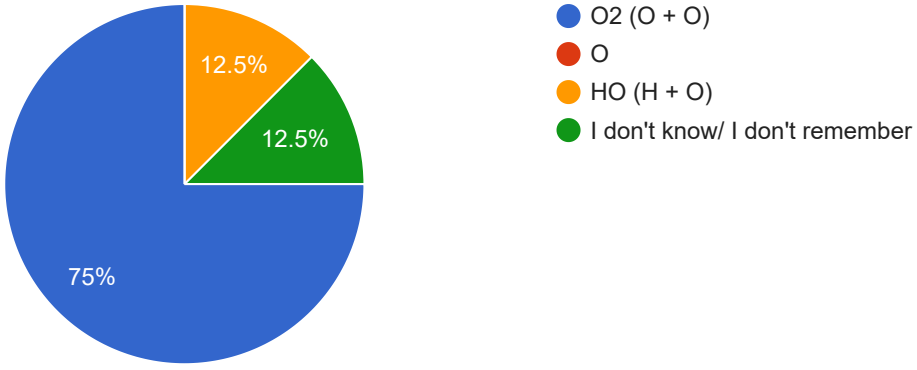
5) What is the chemical formula of water?

8 responses



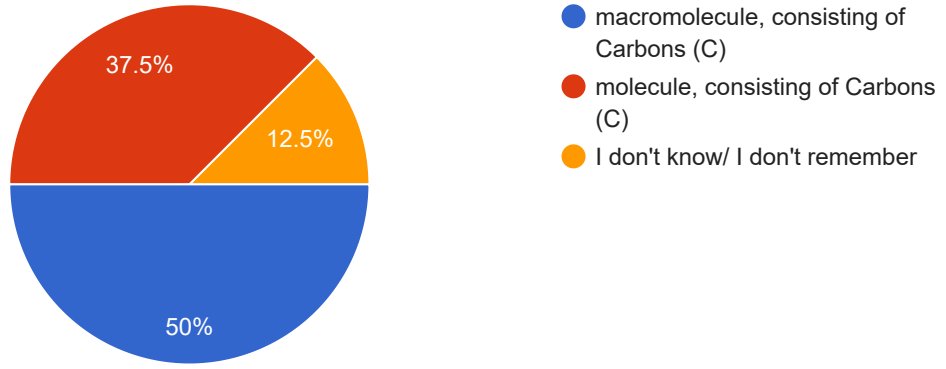
6) What is the chemical formula of dioxygen?

8 responses



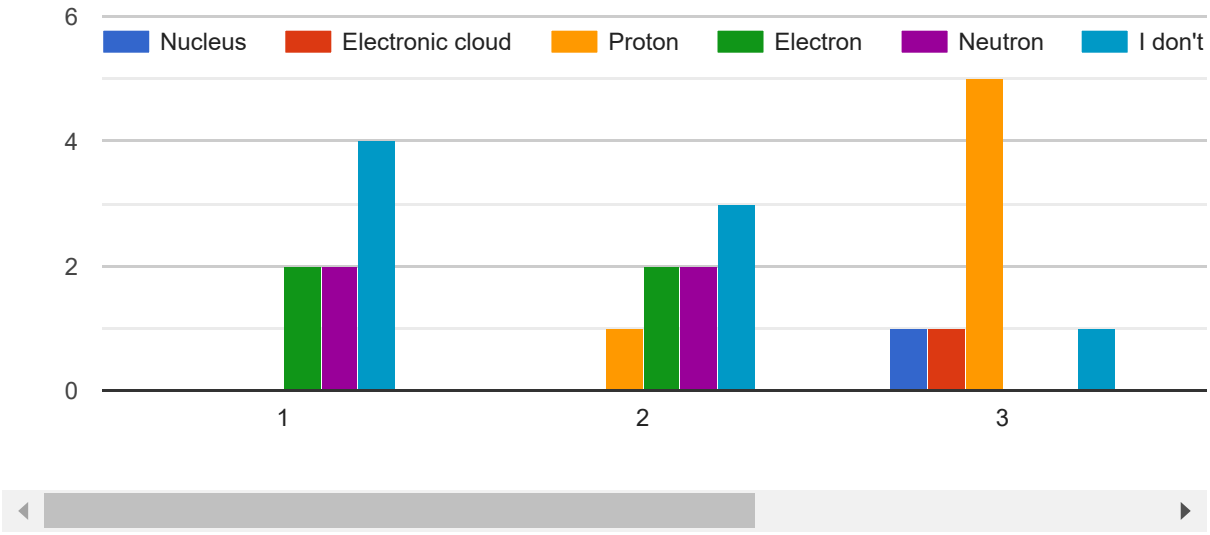
7) The diamond is a...

8 responses

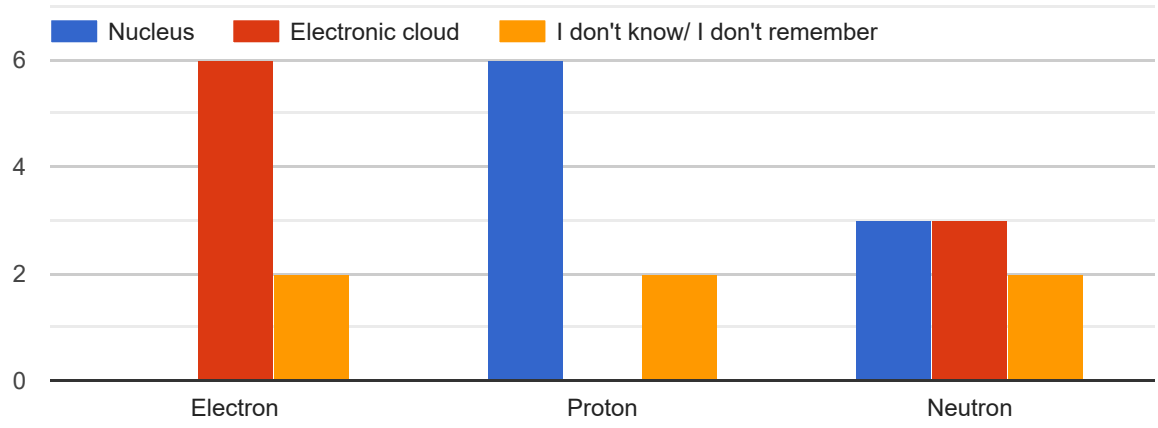


S14) Acquired knowledge (Part 2)

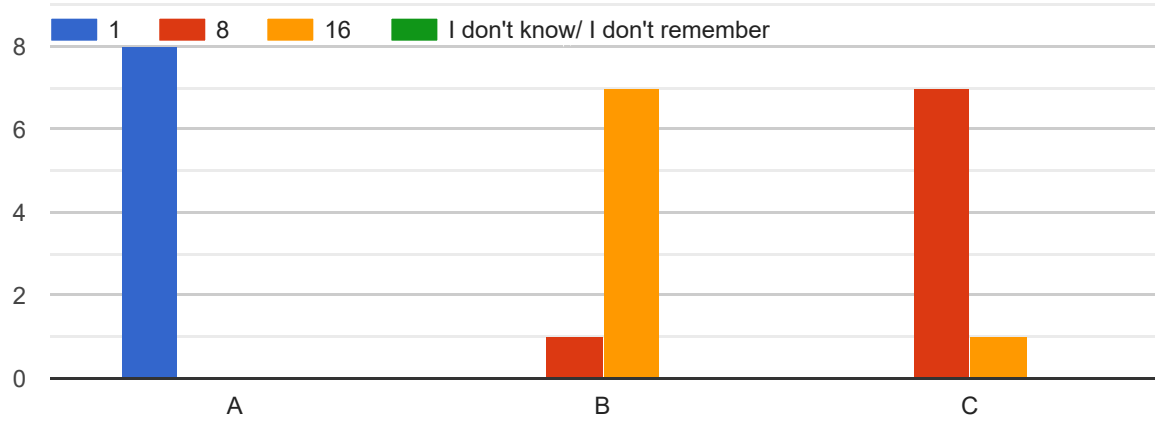
1) Caption the following images:



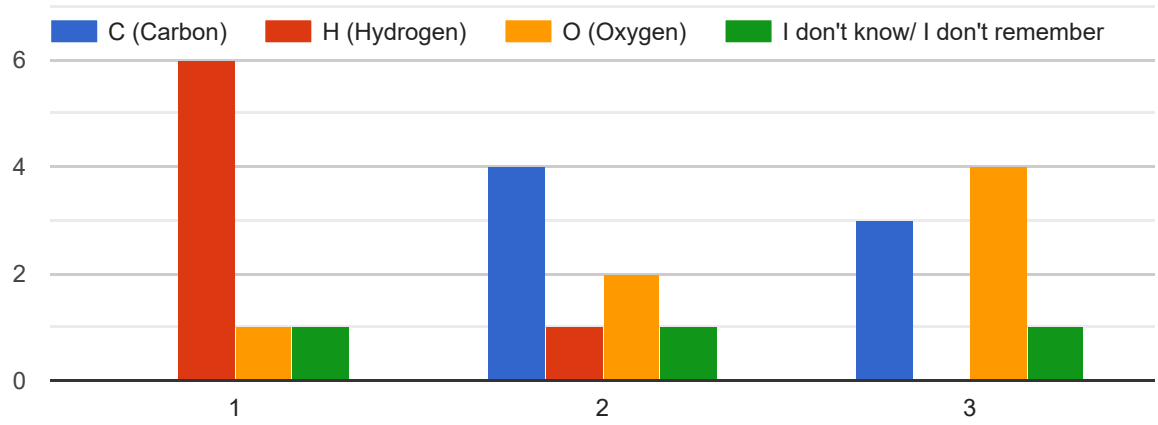
2) Where can we find each of the following particles?



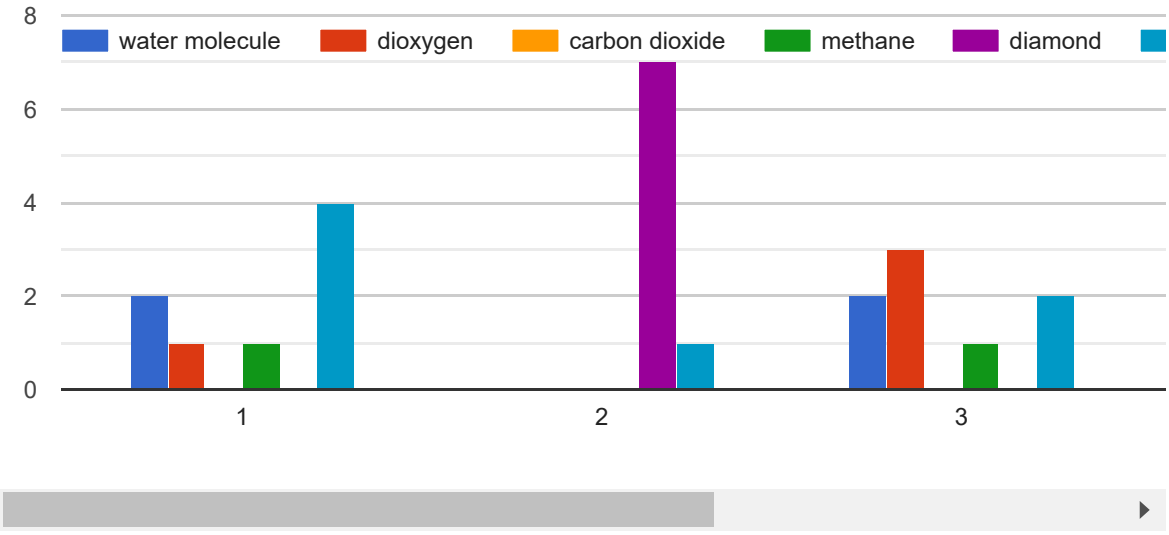
3) What numbers are hidden behind the letters?



4) Which elements are in the following positions of the Periodic Table:



5) The models belong to:



S15) Let's change the world?

1) Both in Lemuria and on Earth, climate change is a very serious problem. Why?

8 responses

I don't remember

There was no snow, there was no water in the lake and there were no flowers.

In the winter she could build snowmen, in the summer water plants and now with climate change she can't do it anymore.

flowers dying

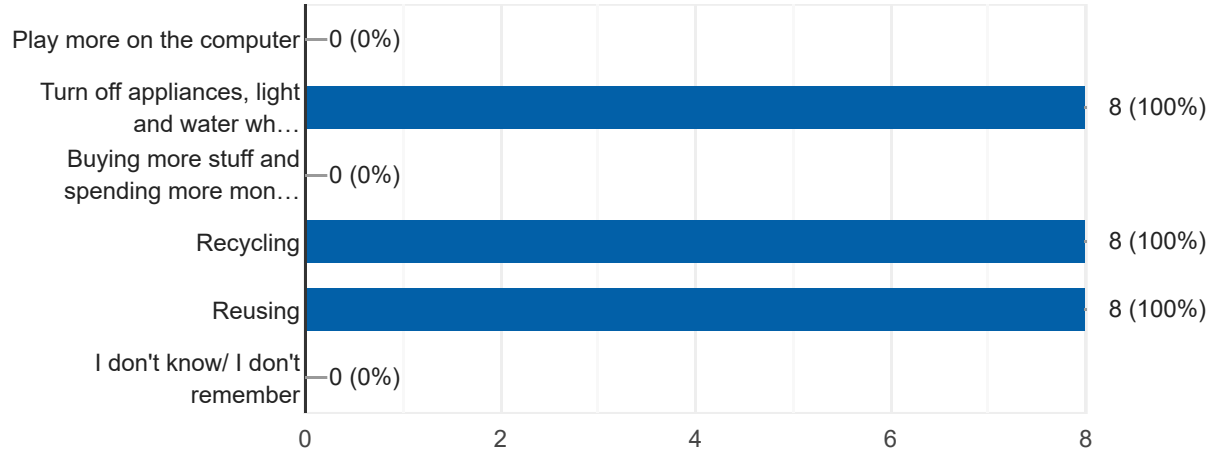
no oxygen in cave

birds stopped singing, the flowers withered, there was no snow

I don't know

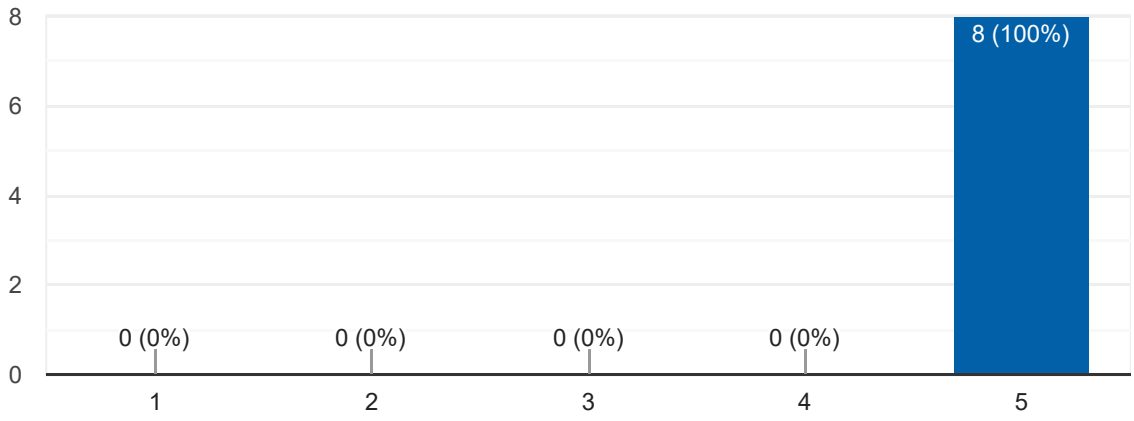
2) What can you do on Earth to soften the impacts of climate change?

8 responses



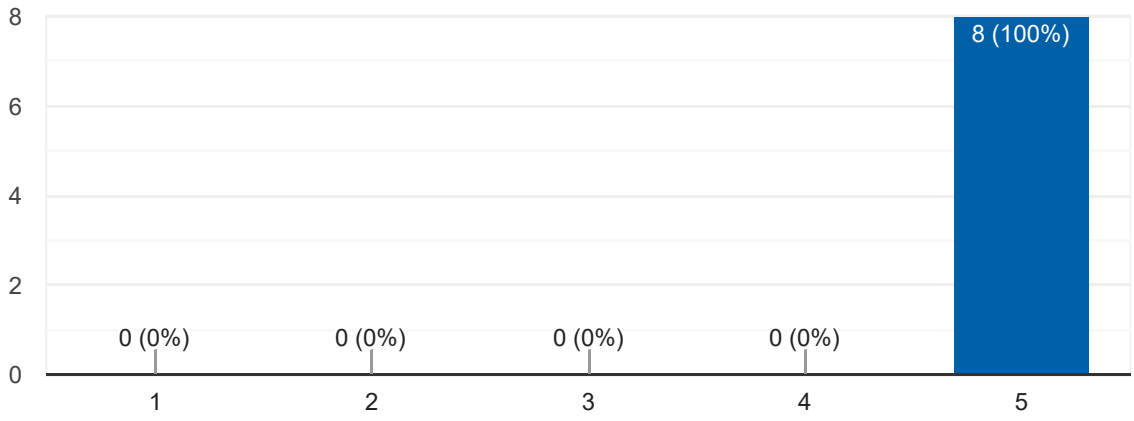
3) How important do you think it is to fight climate change?

8 responses



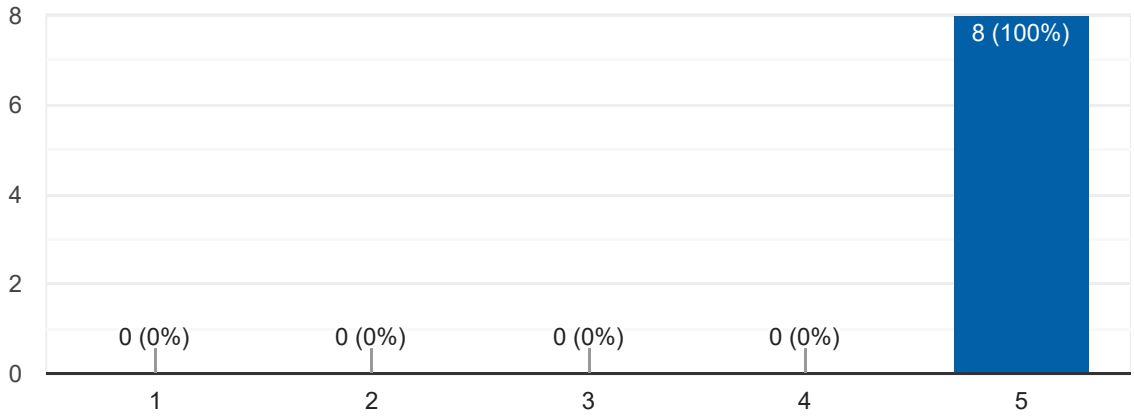
4) Would you like to contribute to not letting climate change attack even more and bring more bad things?

8 responses



5) Now that you've answered all the questions, do you want to play the game again and find out if your answers are right?

8 responses



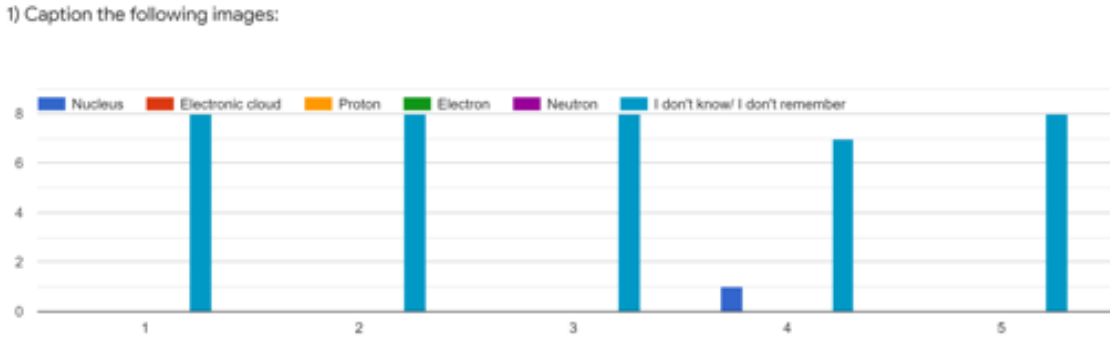


Figure C.1: Questionnaire responses - section 7 question 1

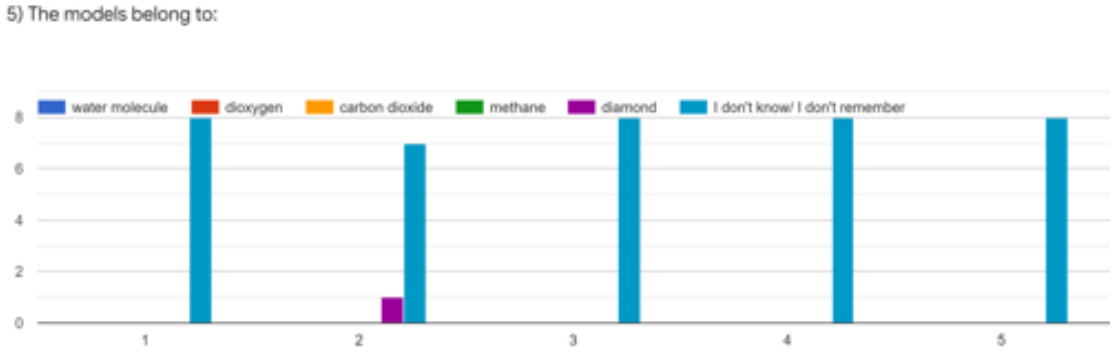


Figure C.2: Questionnaire responses - section 7 question 5

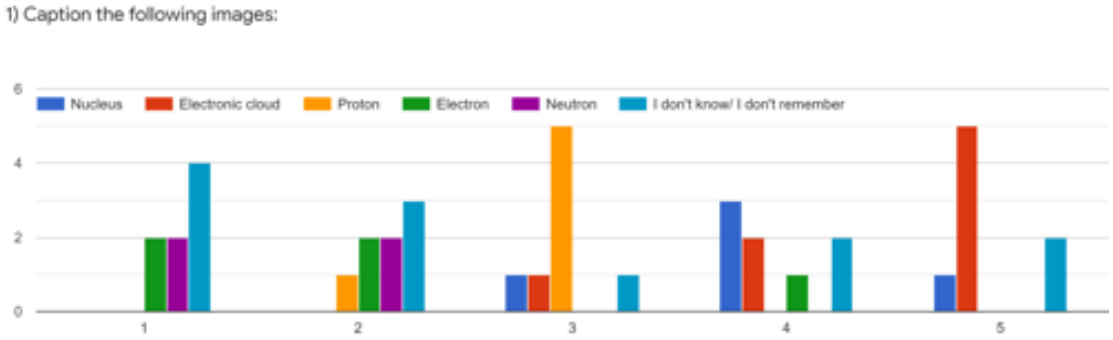


Figure C.3: Questionnaire responses - section 14 question 1

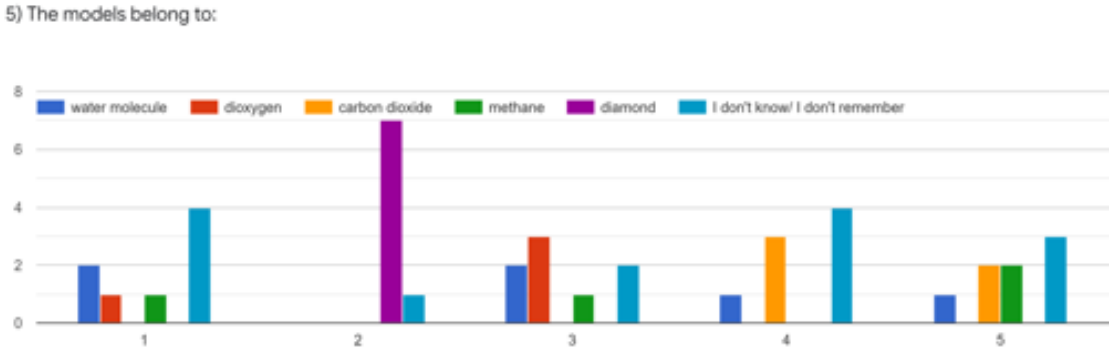


Figure C.4: Questionnaire responses - section 14 question 5