A Custom-Made Board Game to Familiarise Primary School Children With Atoms

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Abstract: To discover the link between the abstract concept of atoms and the macroscopic material world is often seen as one of the key challenges for new students in chemistry. Failing to make this connection results in low student grades, little interest, and eventually small numbers of graduates in chemistry or related disciplines. Science education research approaches this challenge by designing and creating new learning experiences and curricula for children without any prior knowledge about atoms. One promising approach is to introduce atoms and/or sub-microscopic particles in late primary school, such that children can start making connections between the macroscopic and the microscopic world. In this paper, an educational, custom-made board game that combines science content and fun for primary school children is presented to accomplish this difficult task. The board game features cooperative gameplay for 2 to 4 players, simple strategic elements, and play time between 20 and 30 minutes. Intrinsic integration of the learning content was the leading design idea and, as a result, concrete associations between sub-microscopic particles and macroscopic events related to material hardness lie at the core of the game. Another pivotal criterion was that the game is fully playable for children at home, like other board games, or in school lessons. This contribution, therefore, discusses: (*i*) how the game works, (*ii*) the essential design elements of the current game from a designer's and educator's perspective; and (*iii*) the basic atomic concepts which could be facilitated by playing the game. Preliminary play tests suggest that players, or learners, believe the game to be fun, and appreciate the balance between elements of strategy and luck. In summary, a compact, playful activity could trigger children to think of hardness of solid materials as a property that emerges from the strength of interactions between atoms. Such a change in conceptual thinking could in turn ease students' pathway for future chemistry education.

Keywords: board game, atoms, primary school, game-based learning, particulate models, conceptual thinking

1. Introduction

It is widely agreed upon in chemistry education that atomic-molecular theory (AMT) is one of the key concepts necessary to achieve comprehensive understanding of the nature of matter (Gillespie, 1997). When and how AMT should be first introduced in school has generated debate, and some science educators argue whether the teaching of AMT is too complex for primary school children (Fensham, 1994; Wiser and Smith, 2008). However, a series of recent studies provides evidence that children in primary school can indeed grasp aspects of AMT after formal teaching interventions which cover factual knowledge about atoms (Adadan and Ataman 2021; Donovan and Haeusler, 2015; Haeusler and Donovan, 2020; Baji and Haeusler, 2021). Evidently, the (formal) teaching interventions for a coherent learning strategy for AMT must be carefully designed and often face practical difficulties. Firstly, they require trained teachers and plenty of new learning material. Especially, primary school teachers trained in aspects of AMT are scarce since chemistry is not part of pre-service teachers' education. Secondly, schools often want simple, ready-to-go learning materials which connect to themes of current curricula and fit easily into streamlined school timetables. Therefore, novel, compact, and attractive activities informed by educational frameworks for pupils are highly desired, and educational games seem suitable for this purpose.

Although digital games are dominant in research on games for learning, various factors make it difficult to deploy them in classrooms, such as administration and development, teacher expertise and workload, but also the cognitive demand on students. This is typically not the case for non-digital learning environments like board games as they are often compact, self-explaining, and rather inexpensive (Naik, 2014). Moreover, board games have already been reported as valuable learning tools, for example, in various domains in medicine, or when teaching aspects of the solar system (Bochennek et al., 2007; Kirikkaya, Işeri, and Vurkaya, 2010). Thus, a board game could constitute a practical solution for teaching atoms, an unfamiliar concept for primary pupils and teachers alike.

2. Goal of this research

This work presents a custom-made board game which also respects curricular pre-conditions (Figure 1). Our previous experiments showed that children have an intuitive notion of which materials are hard or soft (data not shown). Thus, the game aims to acquaint children with the idea that atoms (*i*) are building blocks of macroscopic objects, and (*ii*) different atoms can form different bonds between them, inducing different levels of hardness in macroscopic objects. From a cognitive perspective, this directs towards thinking of matter as being *particulate* (Wiser and Smith, 2008).
First, the game will be explained. Then, the design process will be outlined from two perspectives: one from educational game design and one from educational theory. The former summarizes and explains the set design criteria, and describes how the board game is inspired by popular commercial board games and builds on established board game mechanics. The latter describes guiding thoughts about how atoms are taught to children without prior knowledge. The most essential elements from both perspectives will be then discussed. Lastly, basic atomic concepts which could be found in children's conceptual thinking after playing the game are suggested by the authors.

Figure 1: The main board with its 5 stations (centred), atom cards and boards for dice and scoring (top), and two exemplary challenges (right)

3. Game description

The board game *Material Monsters* (concept name) is a cooperative resource management game for 2-4 players intended for children in late primary school (age 10-12). The goal of the game is that all players together pass 6, 9, or 12 challenges, for 2, 3, or 4 players within 7 rounds, respectively. For each successful challenge, a corresponding token may be placed into the scoreboard (Figure 1, top).

To pass a challenge, the indicated minimum or maximum dice value must be met when adding up two different dice rolls: *atom* and *bond*. All challenges are related to hardness or softness, for instance, that a monster needs to withstand the fall of an anvil (Figure 1, bottom right). All dice roll differently high, and what dice can be taken depends on which atoms and bonds are placed in the back side of the monster tiles. Players will have to use different combinations for different challenges. There are three kinds of atoms (blue, green, and red), and two kinds of bonds (thin and thick). The red atoms can potentially have two thick bonds, the green ones only one, and the blue ones can only have thin bonds (thin bonds also fit into slots for thick bonds). To take a corresponding dice, a monster needs to be equipped with at least two of the same atom and bond tiles. The only exemption to this rule is that monsters with two atom slots only have one bond slot, so only one bond tile is needed. To start a challenge, all atoms and bond slots need to be filled. However, some challenges require a die roll lower than the indicated value. In that case all bonds may be skipped. It is not allowed to have partially filled atoms or bonds (Figure 2).

Figure 2: Examples for atom and bond placement: the left results in dice for red atoms and thick bonds; the right results in a dice for blue atoms and thin bonds

During the game, the main steps to start a challenge are: (1) scanning the monsters, (2) installing atoms and bonds according to the rules above, and (3) attempting the challenges. All steps take place in different stations, and players have three movements per turn to move between them. The five stations are: (1) one for new monsters to spawn [Entrance hall], (2) one to scan and flip the monster tiles [Scan station], (3) one to insert atoms and bonds [Installation hall], (4) one to receive atoms and bonds for the inventory [Atom slot machine], and (5) one station to attempt challenges [Challenge hall]. After every player had his/her turn, a round ends. Since the next two challenges are visible, the players should discuss the team strategy about which monster attempts which challenge, and which atom and bond tiles might be suitable for each challenge.

In the following example of a two-player game, the course of a potential round is outlined (Figure 3). Player green is first and player red is second. The green player could first move to the Challenge hall with the left monster (1). There, this player could attempt the upper challenge. Since there are two blue atoms and no bonds at all, it is likely to roll rather low. This player could also trade items with player red since they are in the same room. Then, player green could go directly to the Entrance hall to pick up the next monster (2) and bring it to the Scan station for the next round (3). Player red could start by moving to the Installation hall to fetch the right monster which is already filled with red atoms and a thick bond (1) and then go back directly to attempt the upper challenge (2). Finally, player red could stock up his/her inventory by gathering more items with the atom slot machine (3).

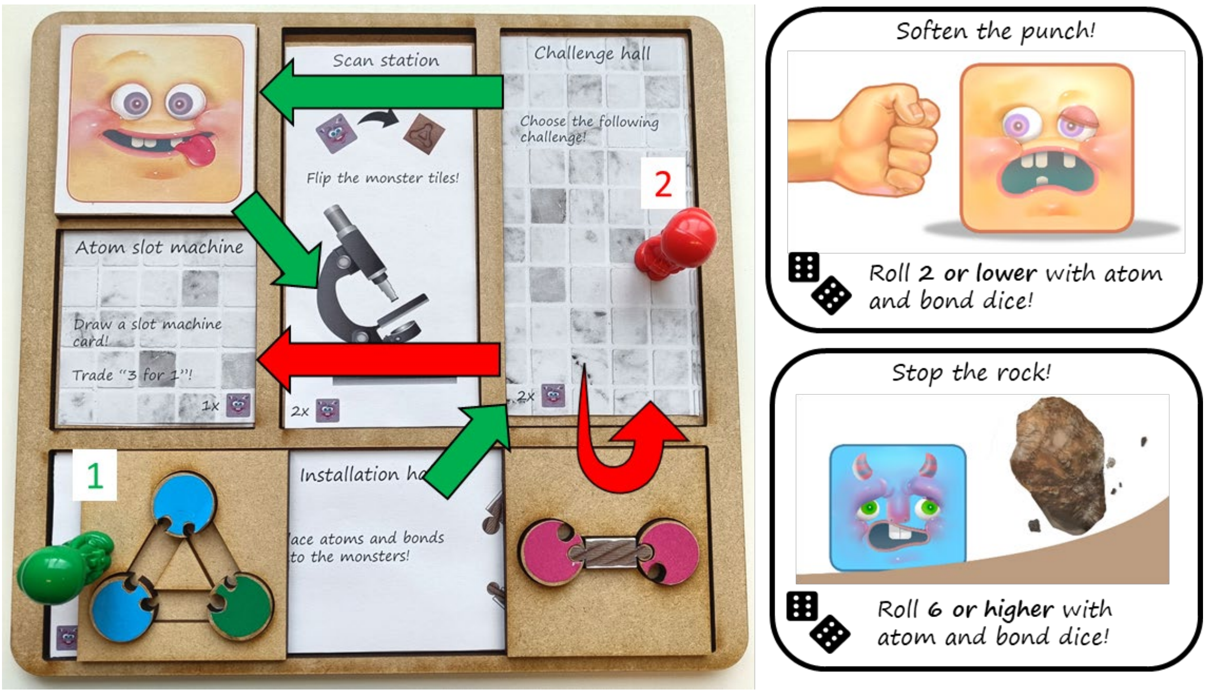

Figure 3: Left: a potential round in a two-player game; right: two challenges of the game

4. The design process

The design process can be seen from two perspectives: one from game design, and one from teaching chemistry. As such, there is an innate difficulty to balance educational content and play, which is pinpointed by an exemplary user review: "For educational purpose I would give this game 8 points. But if I rate it as a board game then I cannot give it more than 6 points" (Staudt Willet et al. 2018, p. 501). Thus, both perspectives show how the current game was designed to achieve learning and fun.

4.1 Influences from educational game design and commercial games

Fundamentally, the concept of 'intrinsic integration' was used as a leading idea to facilitate the balance between educational content and play. Intrinsic integration means that the learning content must be embodied within (*i*) the most fun elements of the game and (*ii*) the structure of the gaming world and the player's interactions with it (Habgood and Ainsworth, 2011). Besides this leading idea, the following other design criteria were set: the game should (1) be cooperative, (2) include strategic elements, (3) encourage communication between the players, and (4) be playable within 20-30 minutes. Each of the set criteria was developed to benefit potential learning for the player. The first three criteria mainly encourage meaningful conversations about the potential take away. If players argue and discuss among each other how available resources are put into place, it is likely they will remember these discussions afterwards. This claim will be validated if a final evaluation reveals successful 'intrinsic integration' of the learning content. The fourth criterion was set to ensure the game stays compact and can be practically played in a school lesson. Having established the leading idea in addition to four other design criteria, it should be outlined how the actual in-game mechanics were derived. That is to guide scientists with little design experience, who are motivated to create other sophisticated games that support players' learning of science concepts.

To initiate the design process, the online portal boardgamegeek.com, and the Dice Tower and its YouTube channel were screened for commercial, non-educational and cooperative board games for children. However, the board games *Forbidden Island* and *5-Minute Dungeon* gave the most impactful inspirations for *Material Monsters*.

In *Forbidden Island,* players have four actions per turn to capture all required treasures before the island, composed of separate board tiles, sinks. Players can cross tiles and have actions, depending on their special class abilities, to achieve this collaborative goal. This game shows several parallels to *Material Monsters*. Similarly, in *Forbidden Island,* players have three movements to contribute to a bigger cooperative process, which is scanning and equipping the monsters to finally attempt challenges. The board similarly consists of different stations/tiles, and the joint objective needs to be achieved within a certain time (counting the rounds). Further, information cards are part of both games to remind players of actions/movements and what can be done in each island tile/station.

In *5-Minute Dungeon*, players fight different sets of monsters with different symbols in 5 minutes. They do this by placing offensive cards matching the symbols of the top pile monster card. Players must argue fast who has the required symbols and play cards accordingly. Once the necessary symbols are matched by all played cards, a monster is defeated. This game gave major inspirations towards preliminary versions of *Material Monsters* for attacking and defence mechanics with atoms, but also to the current version. The concept that monsters are featured in a child-friendly (battle free) design remains unchanged.

On boardgamegeek.com, both *Forbidden Island* and *5-minute Dungeon*, have a medium or high overall rating and a low complexity rating. Moreover, both games are cooperative, can be played within 30 minutes and suit our targeted age range. As such, these well-rounded games gave major inspiration to the design of *Material Monsters* and deserve credit.

Thus far, it was illustrated what game design criteria were set and how in-game mechanics were derived. Now, these criteria and mechanics need to be embedded in the theoretical educational framework to teach atoms.

4.2 Influences from educational theory

In previous tests, primary school children ranked the hardness of materials in a similar order, with steel being harder than stone or wood (data not shown). So, it is assumed that children have an intuitive notion about which materials are hard and which are soft. Although they can describe how to test hardness of materials (e.g., smashing it with a hammer, applying some kind of external force), they cannot explain *why* materials are hard or soft because they are not familiar with the microscopic world. So, we intended to provide a playful activity which should facilitate a meaningful explanation of the hardness of solid materials. In simple terms, the nature of the bonds between different atoms or groups of atoms determines the hardness of solid materials. For a more detailed explanation of hardness, Broitman (2017) provides a critical overview. Thus, the educational goal of the game is to acquaint primary school children with the idea that atoms (*i*) are building blocks of macroscopic objects and (*ii*) the strength of bonds between atoms results in different degrees of hardness of materials. Currently, there is no defined way how to best teach concepts of atoms to young learners that have no prior knowledge of atoms. Generally, it is crucial from an educator's perspective, to avoid teaching misconceptions about atoms. For instance, it has been reported that students erroneously attribute a macroscopic property of the material to the atoms which make up the material (Ben-Zvi, Eylon, and Silberstein 1986). This consideration directly influences visual aspects of the game.

Scholars argue that intermediate atomic models could function as a stepping-stone to acquire more sophisticated ideas about atoms later on, instead of teaching what is scientifically accepted from the beginning (Johnson, 1998; Wiser and Smith, 2008). Such models are, for example, what Johnson and Papageorgiou (2010) describe as Model B, "the particles are the matter, but they have a macroscopic character", or Model C, "the particles are the matter. They do not have a macroscopic character". Further, Model C is described as "[…] properties of state are collective. Particles are drawn and said to be the substance. The properties of a state are seen as collective properties of particles." (Johnson 1998, p. 399). The current design incorporates this idea by framing that there are different atom types which have different capacities to have bonds. It does this by representing atoms as tiles with different colours and big or small puzzle-like slots for the bond. Regarding the bond tiles, two types are used in the game: thin and thick, in the form of small cord shapes (Figure 3). This is to qualitatively represent a weak and a strong interaction and to strengthen the idea that different factors affect the hardness of a material. In this way, it could be concluded that the capacity of a material to withstand external forces depends not only on the type of atoms that compose a material, but how the atoms interact collectively. Overall, this design was deemed to be compatible with Model C.

If primary school children have an intuitive notion of hard and soft materials, the game could direct them towards *particulate* thinking when they discuss with each other what types of atoms might be sufficient for the next challenge. So, this idea is directly connected to the communication criterion.

Lastly, some notes on terminology should be made. From a chemist's perspective, the most important 'stages' of sub-microscopic building blocks of matter are atoms and molecules, and their interactions are usually categorized as intra- and inter-molecular forces (e.g., covalent bonds or Van der Waals forces). When using the more generic term 'particle', it is suggested that children think in a scale of tiny dust particles (Jakab, 2013, p. 1310). In this game context, we prefer 'atom' as the term more likely refers to a single entity (unlike 'molecule' at this scale), and 'bond' which is, chemically seen, a rather generic term.

5. Discussion and preliminary results

The discussion comprises two different dimensions. First, it is discussed whether the game addresses the set design criteria, then explicit design decisions are revisited with regard to the avoidance of misconceptions. Finally, preliminary results should indicate which elements were deemed as fun, which leads to a short outline how the game will be used in future studies.

5.1 Design criteria

The game underwent several (re-) design and test sessions with experts from game design and chemistry education, with 'intrinsic integration' as a leading idea (Habgood and Ainsworth, 2011). In previous versions of the game, structures of atoms and bonds served as upgrades of the strength of weapons, and also as a proxy for defence values. This set up was not pursued since increasing a defence value using different atoms or bonds does not intuitively suggest that a monster becomes harder. Moreover, attack/defence values are upgraded by all kinds of elements in other games such that atoms seemed to be replaceable. In the current version, any fighting mechanic with atoms and bonds was replaced by an equip-and-test mechanic of hardness related events with these items. Now, the success of a challenge is more intuitively translated into which atoms and bonds are installed into the monster. Eventually, it was deemed that the current set up fulfils intrinsic integration of the learning content. This claim is supported by feedback from students who reported the scoreboard and challenges with their simple but sufficient art, as well as sticking atoms and bonds together, were most fun. Nevertheless, it remains arguable whether the game does feature 'intrinsic integration' and if games including fighting elements with atoms promote understanding of the composition of materials.

The criterion of being cooperative has been fulfilled as achieving a certain number of challenges is a clear collaborative goal. Of course, it can be argued whether cooperative games have an educational advantage over competitive games (Wouters and Van Oostendorp, 2013). However, this complex, fundamental change in thinking for each player is mostly independent of in-game performance but more related to the amount of interpersonal interaction. Players are dependent on each other by sharing and trading resources, so collaboration seemed to be supported (Hummel et al., 2011; Hung, Young, and Lin, 2015). Regarding the next two criteria, strategical elements and communication, the principal game mechanic is fairly simple, but it is not obvious for a new player which combination of dice poses a sufficient chance to pass a challenge. Although failed challenges remained the exception during playtests, players must become familiar with expectable dice rolls. As such, players argue which of their items are used best for which challenge as they can always choose between two with a third challenge being face up on the card pile. Thus, the strategy and communication criteria are deemed to be met as well.

Lastly, a playtime of 20-30 minutes was partially fulfilled. Internal playtests have shown that players interact - with sufficient atom and bond tokens to start challenges within 20 minutes. However, finishing a full game highly depends on the experience and absolute number of players. In some playtests, the playtime exceeded 40 minutes. This drawback seems acceptable so long as children are exposed to all the intended game mechanics. Moreover, an incomplete game could spark motivation for students to complete the game at home, or during longer breaks in school.

5.2 Explicit design decisions

Finally, it is important to briefly discuss whether the game avoids introducing potential misconceptions about atoms. As mentioned above, some ideas about atoms might hinder students' progress to more advanced concepts (Pozo and Gomez Crespo, 2005). For example, it is cognitively constraining when learners think that substances are made of tiny particles of the same material embedded in a supporting material like air or the substance itself (Talanquer, 2009). That way of thinking also resembles Model A of Johnson (1998). In a previous version of the game, atoms looked like spheres of sponges, stone, and steel (Figure 4). This feature was initially designed to evoke a connection between atoms and materials, as the game did not specify the composition of the monsters. The monsters only acquire hardness through the rolling of the steel die. To avoid the misconception that atoms are small pieces of macroscopic materials, atoms are now given colours unrelated to familiar macroscopic materials, and each different atom has different bonding capacities. In summary, we expect that the current design has high potential to evoke well-founded ideas about atoms.

Starting to think that the hardness of materials is not inherent (i.e. steel is hard *because it is* steel) but due to invisible building blocks and their interactions is not intuitive but a complex, non-trivial cognitive process (Wiser and Smith 2008, Vosniadou 2019). Thus, it is inevitable that children will need to be confronted with this idea frequently over time. A game or fun activity could provide an optimal opportunity for such kind of learning as it is likely to be revisited.

Figure 4: Tiles for atoms and bonds (left current, right previous version)

5.3 Preliminary results

At this stage, internal playtests with students and pilot tests with primary school children have taken place. Play testers (adults and children) found the challenges, the game's art design, and how to fill the scoreboard as fun and motivating. Besides that, they needed to manage and share resources, gather resources with cards and resolve challenges by rolling dice. This mix of elements seemed to offer a reasonable balance of planning and luck (data not shown). This is supported by quotes during pilot tests. When being asked whether there was something they especially liked in the game, they uttered (translated from Dutch):

Girl (10): I did find it fun and interesting [in general]
Boy (11): I did like to build like that, and yeah, then you could also do challenges like that [...] so I would like to have it at home myself
Boy (11): you only had to see which atom it was and install it like that [...] and I liked that I can choose 3 [referring to atoms]
Girl (12): it was a lot of fun to roll [the dice] and then you were here [pointing to the installation hall] to pick atoms

In conclusion, the game appears to be an enjoyable activity at this stage. Eventually, a player could acquire some basic atomic concepts after playing the game, as suggested by the authors in Table 1. In future studies, using an analytical process similar to that of Stevens, Delgado, and Krajcik (2010), children's utterances after playing the game can be coded to show whether children indeed start to think differently about the nature of materials.

Table 1: Potential basic concepts of atoms after playing the game

Nr.	Basic atomic concept
1	Atoms are spheres
2	There are different types of atoms
3	Different types of atoms have different capacities to make bonds
4	Some interactions are stronger than others
5	Thin/thick bonds represent weak/strong bonds
6	The interaction affects the hardness of the monster
7	The stronger the interaction, the harder the monster
8	Different materials have different atoms
9	Atoms can be mixed in materials
10	There are different compositions of atoms
11	The strength of the bond between atoms determines the strength of solid materials

Nr.	Basic atomic concept
12	The collective behaviour of atoms and bonds determines hardness
13	Hardness, or softness, as macroscopic properties, emerge from atoms

6. Conclusion

With *Material Monsters*, a custom-made board game was created for children to discover atoms and their relationship to material hardness. The game itself and important stages of the design process were presented, and design criteria as well as essential game elements have been discussed from a designer's and educator's perspective. Preliminary results suggested that the game is enjoyable. It was argued that it meets the set criteria. Influences from both design perspectives promise that aspects of particulate thinking can be evoked, but tests with children have yet to confirm these expectations. Therefore, it is planned to conduct game sessions, with pre-, post- and retention interviews with children of late primary school. Moreover, it needs to be shown whether children also want to play it at home, just like other board games, and if they deem it fun. In subsequent iterations, additional components might be added to create a more complex board game. 'Monsters' might be replaced by 'robots' that need to be custom made such that they can make household or work activities more fun or safe as this way of framing might give a more plausible context on why the challenges need to be done in the first place.

Ludography

5-Minute Dungeon, designed by Connor Reid, published by Wiggles 3D. https://wiggles3d.com/5md/;
Forbidden Island, designed by Matt Leacock, published by Gamewright. https://gamewright.com/product/Forbidden-Island

Other resources

Boardgamegeek.com, https://boardgamegeek.com/boardgame/207830/5-minute-dungeon; https://boardgamegeek.com/boardgame/65244/forbidden-island
The Dice Tower, website: https://www.dicetower.com/; YouTube channel https://www.youtube.com/user/thedicetower

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Art for the game was created by freelance artist Pochanun Waenpetch. Icons for the atom picker (installation hall) and the trophy are resources from https://www.flaticon.com. Icons for the microscope (scan station), bond maker (installation hall), and the background for the floor are resources from https://de.freepik.com.

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