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Multi-Material Marbles Game: An Interactive Educational Board Game Incorporating Embodied and Gamified Learning to Attract New Engineers to Materials Science and Materials Selection

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Dr. Bosco Yu joined the Department of Mechanical Engineering at UVic as an Assistant Professor in September 2022. He is passionate about bringing his expertise in solid mechanics and materials design, with a focus on sustainable development, to benefit both his research and teaching activities at UVic. During his education, Dr. Yu developed a strong interest in the solid mechanics of hybrid and composite materials (e.g., CFRP, microlattices). Dr. Yu completed his MASc degree at the University of Toronto, working with Professor Glenn Hibbard. He went on to pursue a PhD at the University of Cambridge, at the Center for Micromechanics. Dr. Yu focused on investigating the mechanics of additively manufactured composites and hybrid materials for use in a wide range of engineering applications. Before joining UVic, Dr. Yu served as a Teaching Assistant Professor at McMaster University from 2020 to 2022, where he played an integral role in curriculum development for materials science education within a project-based learning initiative. His outstanding contributions to materials science education and pedagogy practice were recognized and he was honoured to receive the ASEE - New Materials Educator Award in 2023. Since joining UVic in 2022, as the principal investigator (PI) of the Hybrid 3D lab, Dr. Yu has focused on the research goals of systematically investigating the mechanics of heterogeneous architected metamaterials and demonstrating their strong potential to solve engineering design challenges in a wide range of sectors.

Multi-Material Marbles Game: An Interactive Educational Board Game Incorporating Embodied and Gamified Learning to Attract New Engineers to Materials Science and Materials Selection

Abstract

Materials science is an essential cornerstone of multiple disciplines in the field of engineering. However, new engineering students often lack engagement and interest in learning materials science. To this end, we have developed the Multi-Material Marbles Game, an educational tool designed to introduce students to material properties and materials selection through tactile interaction and hands-on experimentation.

In the game, students measure key material properties – such as mechanical loss coefficient, thermal conductivity, electrical resistivity, and mass density – using spherical marbles made from different families of materials. They then apply these measurements to construct a Material Property Chart (Ashby plot). The tactile hands-on experience of the material marbles helps foster an understanding of how different materials behave. The game also illustrates the thought process behind materials selection, a critical aspect of engineering design. By engaging learners in this physically interactive experience, the game aligns with the principles of experiential learning, where knowledge is acquired through active participation rather than passive observation. This gamified approach not only makes materials science more accessible but also bridges the gap between theoretical concepts and practical applications in engineering design. The game incorporates a variety of Universal Design for Learning (UDL) principles that have been shown to improve learning outcomes for all people.

The Materials Marbles Game is adaptable for both classroom use and outreach initiatives, making it an effective tool for high school seniors, first-year engineering students, and public engagement events. Results from pilot studies show high levels of student engagement and an increased interest in exploring materials science further. All elements of the game (e.g., CAD design, game instructions, material information cards, materials/equipment list) are open source, allowing educators and outreach event organizers to download the information and implement the game in their classrooms.

1. Introduction

Materials play a pivotal role in advancing the technologies that shape modern society, both from understanding the connection between a material's structure, properties, processing, and performance in the field of materials science and selecting the correct materials for a particular design. Despite their significance, materials science as a field is often introduced later in engineering education – generally in the second year of university studies, following first-year general engineering courses. At that point, students have already established their academic focus and are less likely to appreciate how the study of materials science can play a role in their future careers. Additionally, most educational institutions rely on traditional lecture-based approaches to teach materials science, resulting in a disconnect between foundational STEM concepts and the practical relevance of material properties and selection. This gap is particularly evident in outreach initiatives aimed at inspiring the next generation of engineers. Traditional lecture-based approaches often fail to captivate and engage younger audiences or non-specialists, who benefit more from interactive and tangible learning experiences [1-3]. This challenge underscores the need for innovative educational tools that showcase core principles of materials science[4].

Gamified learning has emerged as a transformative educational approach, incorporating game elements to foster engagement, motivation, and deeper understanding [5-6], with Deterding et al. defined gamification as the use of game design elements in non-game contexts [7]. Adapting this definition to the context of STEM education, we generated a gamified learning design space, as shown in Fig. 1. Qualitatively, educational gamification tools involve two engagement attributes: the so-called gamefulness [8] and playfulness [9-11]. Gamefulness refers to game-like elements such as structure, rules, and goals. Meanwhile, playfulness (or playful interaction) refers to lightheartedness, creativity, and fun or thought-provoking interactions. For instance, at the extreme ends of this spectrum, traditional lectures are low in both gamefulness and playfulness, STEM competitions are high in both attributes, and 'serious games' represent the use of a complete game for educational purposes. In practice, all educational games involve various degrees of playfulness and gamefulness, see Fig. 1.

When combined with experiential and active learning methods, gamified strategies have demonstrated significant improvements in learner outcomes [12-16]. These approaches emphasize "learning by doing," which has been shown to reduce failure rates and enhance knowledge retention across diverse educational settings [17-21]. The interactive and cooperative nature of gamified learning aligns well with the cognitive and social processes that underpin effective education, making it particularly well-suited for outreach activities aimed at generating interest in materials science. By integrating playful interaction, learners can intuitively engage with complex concepts through hands-on experiences. Elements such as collaboration and problem-solving foster curiosity and exploration, encouraging learners to experiment with ideas and apply theoretical knowledge to practical scenarios. Understanding the relationships between material properties, structure, and applications requires both theoretical knowledge and practical insights; gamified and playful learning approaches are uniquely effective in bridging the gap between these domains.

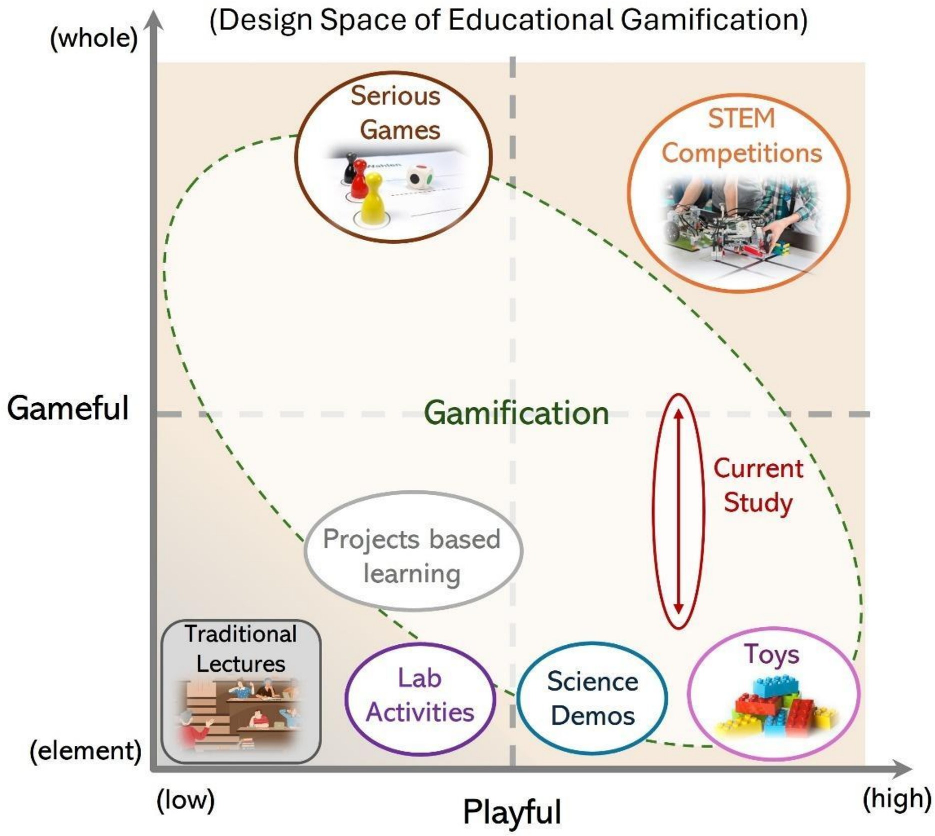

Fig. 1 A design space of playfulness versus gamefulness in STEM education, adapted from Deterding et al. (2011). The Multi-Material Marbles Game developed in this study occupies a position between an educational game, a science demo, and an educational toy. (Note: The axes are qualitative, and the plot is intended for illustrative purposes only.)

Despite the demonstrated benefits of gamified and interactive learning, there is currently a lack of interactive tools that effectively communicate and present materials engineering concepts in university outreach settings. Existing props and demonstrations often fail to capture the interdisciplinary nature of materials science or engage diverse audiences in a meaningful way. This gap highlights the need for a versatile and accessible educational tool that can convey the importance of material properties and selection through interactive and hands-on experiences. Such a tool would not only enhance outreach efforts but also bridge the gap between academic concepts and real-world applications, inspiring interest and understanding among prospective engineering students.

1.1 Scope of study

In this study, we propose and implement an educational board game, the Multi-Material Marbles Game, to capture the essence of materials science. The Multi-Material Marbles Game developed in this study occupies a position between an educational game, a science demo, and an educational toy (see Fig. 1). This game offers an innovative, gamified educational experience that introduces learners to the core principles of materials science and engineering, especially material properties.

It is important to note that the inclusion of playfulness and game-like elements does not automatically ensure an activity has educational value or effectiveness. Educators must take responsibility for ensuring that the activity has clear learning objectives, while gamification enhances engagement without compromising the delivery of these objectives. (An educational game that is too entertaining may inadvertently become purely recreational, undermining the intended learning outcomes.)

In the remainder of this study, we will:

1. Present the intended learning objectives of the game.
2. Explain the game mechanics, as run in the study in Sections 3 and 4.
3. Discuss a student survey evaluating the educational effectiveness of the Multi-Material Marbles Game. Through this survey, we also offer recommendations for the target audience of this educational game.

Finally, the Multi-Material Marbles Game is fully open-source and freely available, enabling educators to customize and implement it in classrooms or outreach activities. All components of the game – including CAD designs, instructional materials, and a detailed facilitator guide – can be found linked here [22]. Details on how the game was packaged for dissemination, including the creation of a "simplistic" version for early K-12 classrooms, can be found at the end of this paper.

2. Educational Game Design and Mechanics

2.1 Goal and Learning Outcomes

The goal of the current study is to develop a new educational game that can effectively communicate the key design philosophies (i.e., the essence) of materials science and engineering to new engineering learners, such as high school students or 1st-2nd year undergraduates. Table 1 summarizes the goal, game objectives, and potential learning outcomes of this Multi-Material Marbles Game.

The key design philosophies in materials science and engineering can be viewed from both a bottom-up (science-led) and top-down (design-led) perspective [23]:

- **Bottom-up view:** Different materials exhibit distinct material properties due to variations in their chemistry, atomic structure, and microstructure – factors that can also be influenced by the material processing route. These differences in material properties lead to variations in engineering performance, a relationship known as the process-structure-properties-performance (PSPP) relationship.
- **Top-down view:** The PSPP relationship can also be viewed in reverse. Materials engineering is an applied science field aimed at enhancing engineering performance through the selection of suitable materials, manufacturing processes, and the atomic structures of materials at microscopic to even nanoscopic scales.

While both perspectives are valid and convey the same underlying information, the top-down view aligns more effectively with the "known-to-new" communication guideline, which is particularly useful when introducing new topics to beginners. This approach begins with familiar concepts - such as the measurement of engineering performance and the associated material properties - before introducing the concepts of the material properties design space (and perhaps the approach of materials selection), followed by diving into the details of materials science at the atomic level. Furthermore, we aim to design an activity that allows learners to experience the learning outcomes, enabling them to embody the learning process rather than simply receiving facts.

Learners who are interested in STEM are already familiar with the scientific method and measurements. As a result, we developed a multiplayer educational game that involves measuring the materials properties of different materials. The game is designed to introduce players to the following key concepts in order from "known-to-new" [24]: 1) performance versus materials properties, 2) different materials have different properties, 3) the material properties chart as an engineering design space, 4) materials selection at a high level[1] and 5) material properties can be affected by chemistry and microstructure[1] These concepts are summarized in Table 1.

Table 1: Goal and Potential Learning Outcomes of the Multi-Material Marbles Game

Goal	Introduce newcomers to key concepts in materials science engineering via a quick and interactive activity
Potential Learning Outcomes	1. Distinguish between the similarities and differences of performance versus material properties 2. Experience how different materials have different materials properties 3. Recognize materials properties charts and their role in the engineering design space 4. Appreciate the process of materials selection[1] 5. Appreciate that material properties can be affected by chemistry and microstructure[1]

2.2 Game Mechanics

The physical apparatus of the Multi-Material Marbles Game consists of two groups of equipment: 1) multi-material marbles game board, and 2) properties measurement devices, see Fig. 2. All items can be easily obtained via e-commerce purchases and in-house 3D printing and laser cutting.

1 Readers should note that the potential learning objectives 4 and 5 are covered through the game supplementary documents indirectly instead of from the game activities.

Game Rules: In this game, two players (or teams) collect data to measure the properties of various material spheres and then construct a material properties chart using a grid as a game board . The gamemaster (GM) determines whether the players will work on a 5×5 or 12×12 board (Fig. 3a-b), depending on the time available for the event. The GM also assigns two material properties to represent the X and Y axes of the game board. The players will receive 2 testing plates (2"×2"×3/8") and 3 balls for each material, so that they may measure material properties such as mass density, mechanical, thermal, or electrical characteristics (Fig. 2). Each player is responsible for measuring one property and ranking the materials from low to high by placing 1 ball for each of the materials on a ranking bar that represents one axis of the grid (Fig. 3c-d). After the individual measurements are complete, the players collaborate to construct the main game board by placing the third ball of each material at the appropriate intersection point on the chart (see Fig. 4).

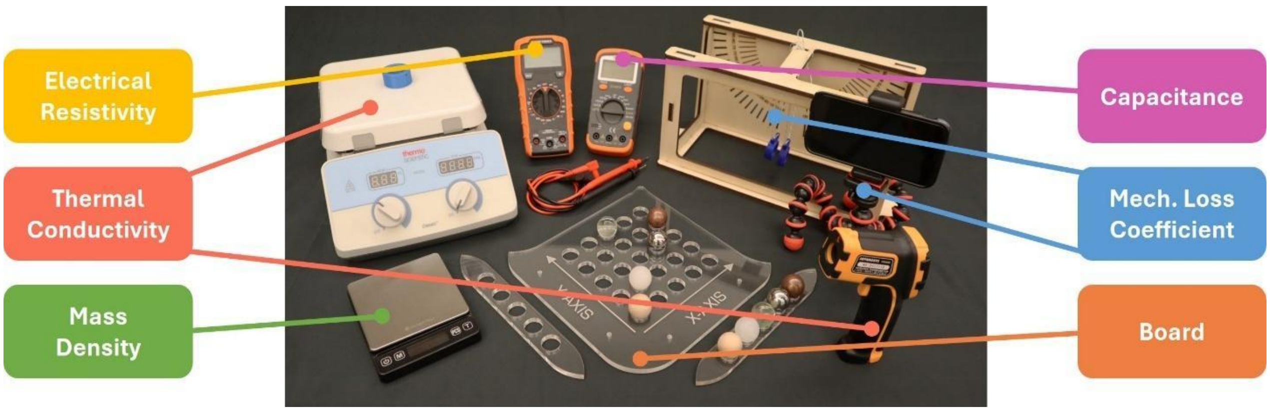

Fig. 2 The physical apparatus of the Multi-Material Marbles Game

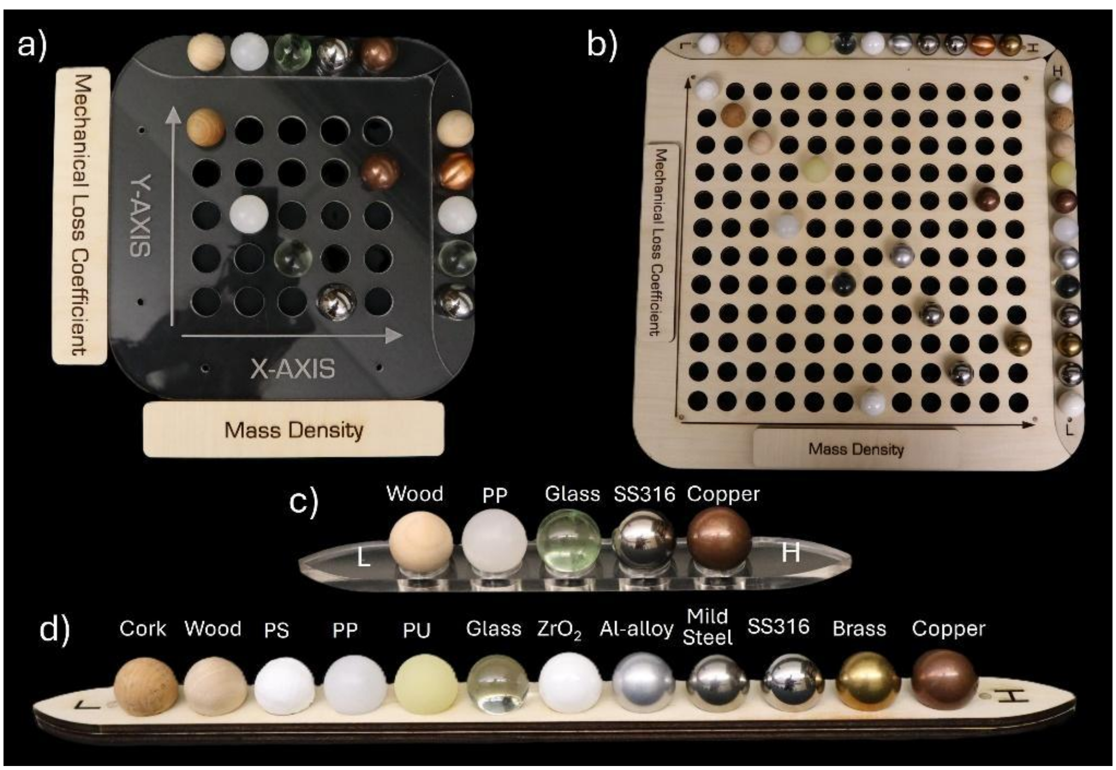

Fig. 3 Multi-Material Marbles Game: 5x5 and 12x12 Game Boards (a-b), and material ranking bars (c-d).

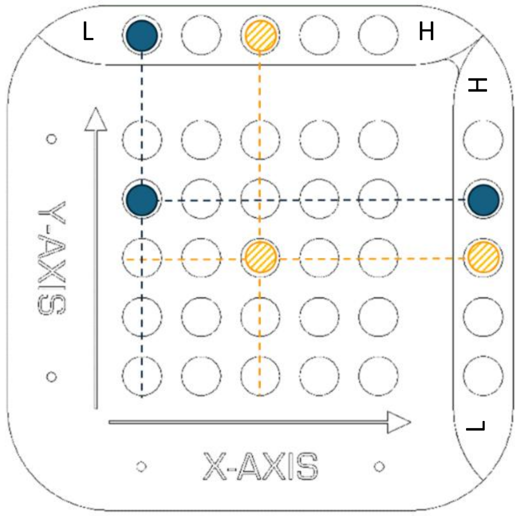

Fig. 4 Construction of the materials properties chart.

Multi-material Marbles: The Multi-Material Marbles Game includes spheres made from various materials, such as natural materials (cork, wood), polymers (polystyrene, polypropylene, polyurethane), ceramics (silica glass, zirconia), and metal alloys (aluminium alloys, mild steel, stainless steel SS316, brass, and copper), as shown in Fig. 3. These spheres can be easily sourced through e-commerce ball bearing vendors. To align with Potential Learning Objective #1, all spheres were selected to be fully dense and of uniform diameter (D = 1”).

This setup allows educators to emphasize the similarities and differences between physical properties, engineering performance, and material properties. Particularly (talking point 1): *"A material property is an inherent characteristic of a material that does not depend on size (e.g., mass density). In contrast, physical properties (e.g., mass) and engineering performance (e.g., stiffness) depend on size. Materials engineers often measure engineering performance and then normalize it by size to determine material properties (e.g., density = mass/volume)."* By ensuring that all spheres are fully dense and identical in size, players can compare materials directly, eliminating the influence of geometry on the observations.

Game Board: The game board is an $N \times N$ matrix where players place the balls within the grid. Currently, we have explored N = 5 and 12, as shown in Fig. 3c-d. Educators can select their own combination and variety of material spheres based on their budget and available supplies. Please refer to the game link [22] for the DXF file of the game board.

Material Properties Measurement: Educators can select their own measurements of material properties based on the tools and equipment available to them. So far, we have explored the material properties shown in Table 2. Note that from our initial test, we discovered that the measurement of some of the material properties (such as hardness, thermal conductivity, electrical resistivity, and dielectric constant) is much more consistent when measured on a flat plate (say consistently 2”×2”×3/8”); thus an additional testing plate per material should be prepared to be given to each of the players. The purchase list is included in the game link [22].

Table 2: Material properties and associated measurement devices.

Property Group	Material Property	Physical Property	Equipment
Physical	Mass density ρ (g/cc)	Mass (g)	Digital scale
Mechanical	Yield strength σ_Y (MPa)	Hardness (Mohs)	Mohs hardness kit
	Mechanical loss coefficient ξ (-)	Angle changes (°)	Newton's Cradle and cell phone camera
Thermal	Thermal conductivity k (W/m·K)	Degree changes (K)	Ice, Thermometer
Electrical	Electrical resistivity ρ (Ωm)	Electrical resistance (Ω)	Multimeter
	Dielectric constant ε_R (-)	Capacitance (nF)	Capacitance meter

Game Solutions: After the players have constructed the material property chart, the GM will then reveal the solution to the players. The solution may be revealed using a large printout (e.g., 12”×18”) where the image of the game board is in 1:1 scale, so that the players can place their own chart onto the solution and see if their measurements were correct. An example of the solution printout can be seen in Fig. 5.

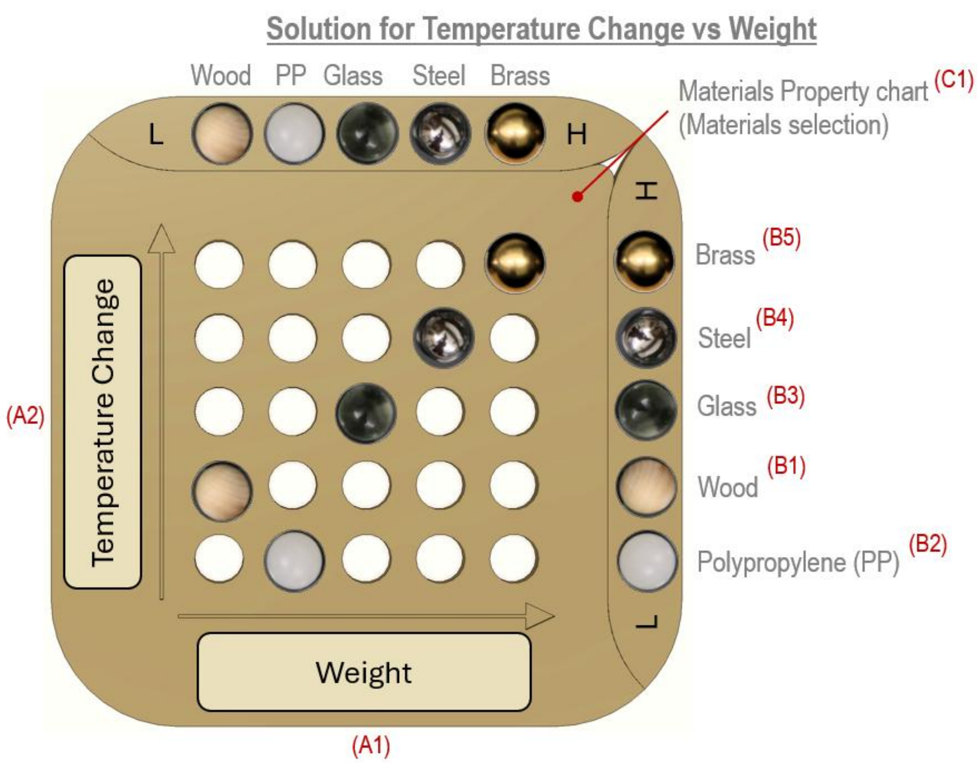

Fig. 5 An example of the solution printout. The red labels (A1, B2, etc.) indicate discussion points for players and the GM to further explore using the supplementary material properties flash cards.

Supplementary Reading Materials: After the solution has been revealed, the solution manual printout also shows additional labels (see Fig. 5) that indicate discussion points for players, guided by the GM, to further explore the supplementary documents such as the material properties flash cards and the materials selection flash cards (see examples in Fig. 6 and 7, respectively). It is worth noting that some of the properties in this game are intentionally more advanced so that educators can have additional discussions with the players after the activity (e.g., *What is the mechanical loss coefficient and the dielectric constant? What causes one material to have a higher dielectric constant than another?*). These flashcards are designed so that interested players can get additional context about the underlying materials science of various materials and their properties, as well as the process of materials selection in engineering design. For the full set of the material properties flashcards and the materials selection flashcards, please refer to the document reference link above.

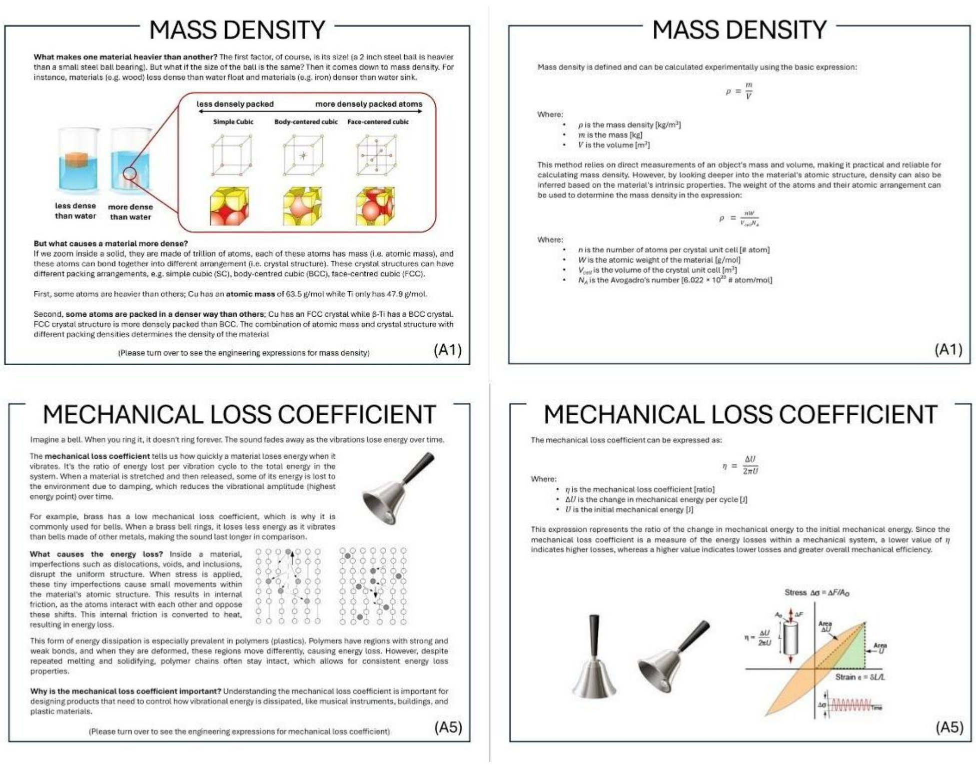

Fig. 6 Example of material properties flash cards used during the study.

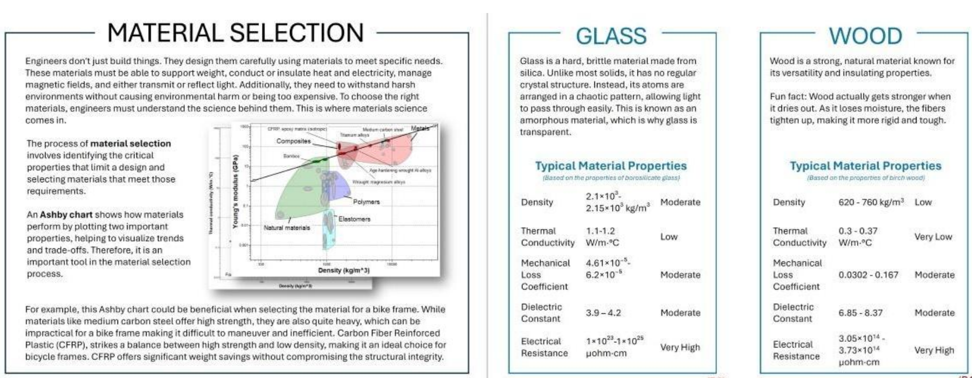

Fig. 7 Example of material selections flash cards used during the study.

Additional Activities on Materials Selection: For a more advanced cohort (e.g., university students), the educator may also utilize this Multi-Material Marbles Game to introduce students to the materials selection process. For instance, the GM may ask the students to recreate the quantitative materials properties chart using engineering design tools such as Ansys Granta EduPack™, a teaching software for materials education [25], see example in Fig 8. The educator can follow by teaching additional content such as the material performance index, with various case studies (e.g., mechanical design and materials selection of a lightweight bike frame versus a cost-effective bike frame).

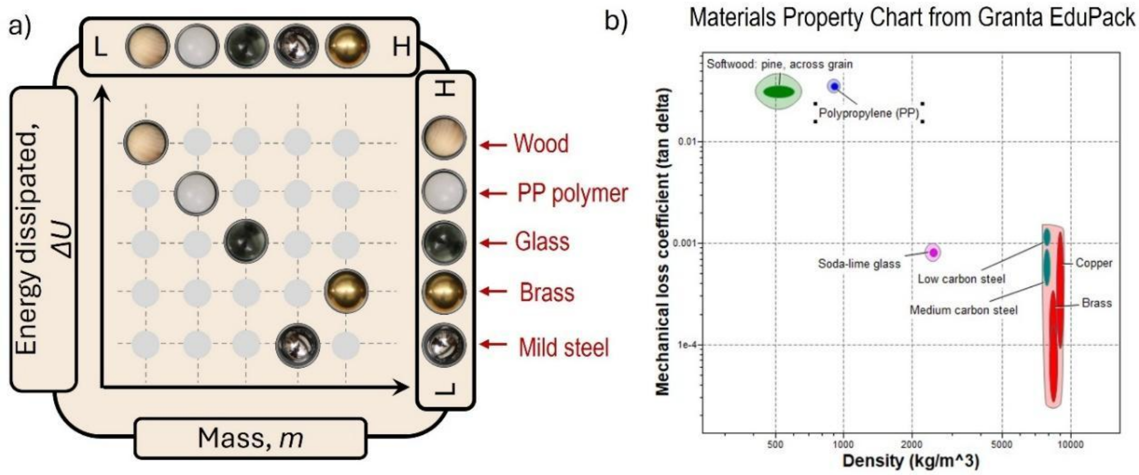

Fig. 8 Examples of: a) physical qualitative versus b) computer-generated quantitative material property charts.

Game Mechanics Variation with Enhanced Gamification Element: Currently, the Multi-Material Marbles Game is designed as an activity that encourages playful interaction to achieve the potential learning objectives. The tactile nature of the multi-material spheres and the opportunity to collaborate with other players keep participants engaged throughout the experience. Although there are "game mechanics", the activity currently does not have the concept of a "winner". Under Deterding et al.'s taxonomy of gamification, this game lies between an educational game, a science demo, and an educational toy, see Fig 1. We believe this achieves a good balance between keeping the game lighthearted and delivering the learning objectives. Having said that, we encourage other educators to explore other potential benefits of further gamifying this activity. One possible way to enhance the game-like elements of this activity is to add a competitive aspect. For example, creating a scoring system to assess the construction of the material properties chart (both in terms of speed and accuracy) would allow different teams to compete against each other. However, educators should also assess whether enhancing the gamefullness has a potentially negative impact on the delivery of the learning objectives (for instance, if the focus on competition distracts from the educational aspects of this activity).

Game Implementation: The Multi-Material Marbles Game is designed to be flexible, making it an excellent tool for introducing materials science to various audiences, including high school students or 1st-2nd year undergraduates. Educators can make minor modifications to tailor the game to their specific audience. For example, a standard 5×5 game board with supplementary material flashcards can be used in a K-12 classroom setting. A more advanced version of the game, which includes a materials selection tutorial, can be implemented in a 1st or 2nd year undergraduate classroom. Finally, the full 12×12 game board can be used as a physical demonstration of material science and materials selection, serving as an engaging icebreaker for recruiters at an outreach event.

3. Implementation Test Group and User Survey Feedback

3.1 Implementation Test Groups

Two separate trial runs of the Multi-Material Marbles Game were recently implemented in the Mechanical Engineering Department at the University of Victoria. At this university, engineering students are generally not introduced to materials science until their second year of studies. Therefore, the target audience for this year's trials was the second-year engineering cohort. To assess the effectiveness of the game in introducing materials science concepts to newcomers, we implemented it in two distinct courses: the second-year *Introduction to Materials Science* course (MECH 285) and the fourth-year *Materials Selection for Sustainability* technical elective (MECH 424). This allowed for a cross-comparison between the experiences of first-time learners and more advanced students, providing valuable insight into the game's effectiveness with cohorts of varying levels of prior knowledge. The feedback survey for the second-year cohort included 72 participants (80% of the class), while the feedback survey for the fourth-year cohort had 21 participants (50% of the class).

Since the second-year engineering students generally had no prior knowledge about materials science, the Multi-Material Marbles Game for this cohort was complemented by an additional lab activity on material properties charts. Immediately after completing the material properties charts within the game, GMs guided learners to replot and compare the same charts using Ansys Granta EduPack™ in a computer lab (see example in Fig. 8). This provided the learners with more in-depth insights about material properties and introduced them to the concepts of materials selection.

3.2 Survey Questionnaire

Ethical approval of the survey was obtained from the University of Victoria Ethics Board (Protocol# 24-0472). The survey includes questions regarding the students' experiences in the materials science tutorials. Students were sent a survey link via email through the University-approved software SurveyMonkey, whereby students could decide to participate in the short survey and submit their answers anonymously. To mitigate instructor influence on survey results, the survey link was sent out by neutral third-party administrative staff and not by the course instructor. The survey was created such that learners would be able to reflect on their experiences after they have played the Multi-Materials Marbles Game. Below is the complete list of survey questions.

(Q1-Q7: 1 strongly disagree --------- 5 strongly agree)

1. Before this activity, I had a clear understanding of materials science.
2. Before this activity, I had a clear understanding of the materials selection process.
3. This activity helped me better understand materials science.
4. This activity helped me better understand the materials selection process.
5. This activity increased my interest in learning more about materials science.
6. This activity (including the reading materials) helped me better understand the materials selection process.
7. How engaging did you find this activity? (1 = Least engaging, 5 = Most engaging)
8. Please provide a comment on one aspect of the activity you enjoyed.
9. Please provide a comment on one aspect of the activity you suggest for improvement.

4. Survey Results & Discussion

Figure 9 summarizes the survey results (Q1–Q7) for the second-year and fourth-year cohorts, respectively. Meanwhile, Table 3 highlights selected student comments for Q7 and Q8.

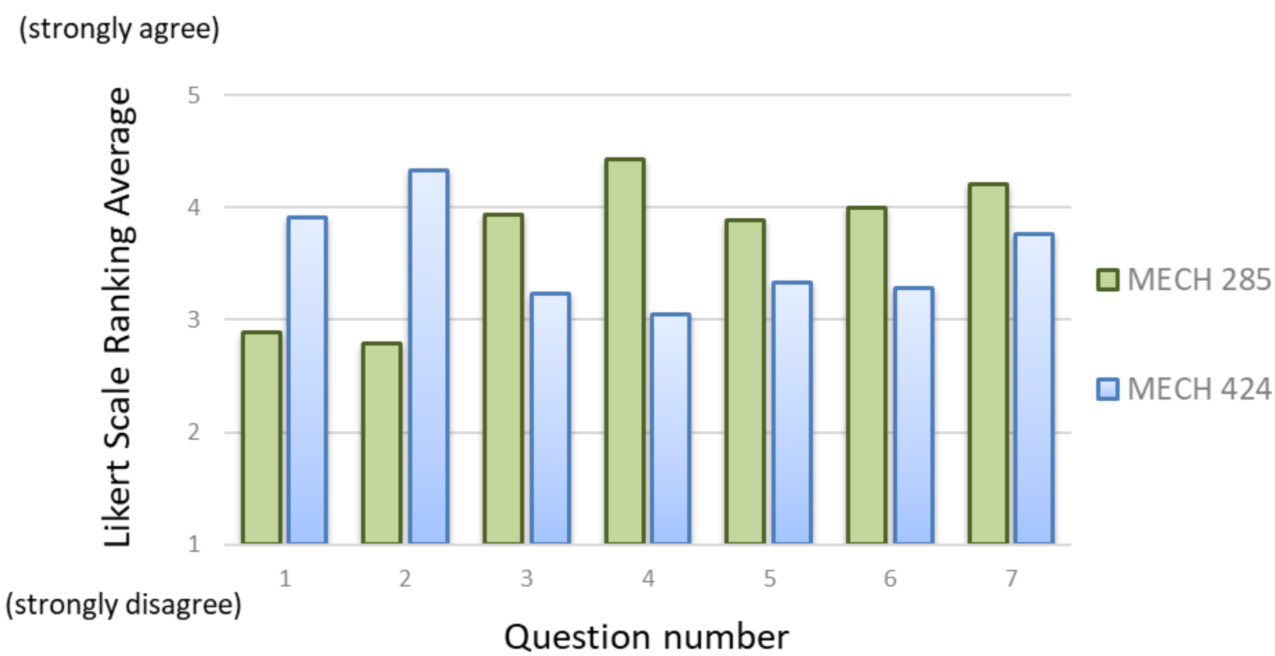

Fig. 9. Summary of survey results for Questions 1-7. Likert scale ranges from (1) strongly disagree to (5) strongly agree.

The feedback from the second and fourth-year cohorts was generally positive; see Fig. 9 and Table 3. For the second-year cohorts particularly, the Multi-Material Marbles Game was introduced at the beginning of the term when learners had no prior knowledge of materials science. Thus, the second-year cohort predominantly found this educational game effective in helping them better understand materials science, material properties charts, and materials selection (through the complementary activity linking to the Granta EduPack software). The second-year cohorts also found the activity particularly engaging and fun, see Q7 and Fig 9 and Q8 comments in Table 3.

The feedback from the more advanced fourth-year cohort was also positive. However, the Multi-Material Marbles Game was less effective in helping the learners compared to the second-year cohort. This outcome was expected, as the activity was implemented near the end of their undergraduate education when students were already well-versed in materials science concepts, PSPP relationships, and materials selection strategies. In fact, Comment #3 shown for Q8 for the fourth-year cohort (see Table 3) supports our hypothesis, suggesting that the Multi-Material Marbles Game serves better as an introductory educational tool rather than as a reinforcement tool for advanced learners.

Overall, the results from the surveys and student feedback are quite promising, showcasing the engaging and interactive nature of the Multi-Material Marbles Game. Both the second-year and fourth-year cohorts highly appreciated the hands-on, experimental aspects of the game. In fact, the second cohort suggested that the activities can be further expanded (both in terms of the number of materials in the game and the duration of the activity) so that they can learn the topic in more depth through this educational game.

The positive comments from the fourth-year students highlighted the potential of the game as an engaging educational tool, even though it may be better suited to introductory learners. The feedback shows that the game effectively stimulates interest and promotes a deeper understanding of material properties and materials selection, offering great potential for refining and enhancing the learning experiences for future students.

Table 3: Selected student comments for Q8 and Q9.

Q8 Comments (2nd yr) *[comment on one aspect of the activity you enjoyed]*	**1.** I like the physical demonstration. I understand that although it can be difficult to teach material sciences in a hands-on way as it is rather theoretical, I think that the demo we did gave a good hands-on understanding of properties. I like the little flip cards with a description of each property. **2.** I like the hands-on aspect of this lab. How we were able to perform our own tests and see the results of these tests was quite satisfying. **3.** I enjoyed using the various tools. The hands-on nature of the activity was quite nice. **4.** I enjoyed the scratch [Mohs hardness] test as it seems primitive but gives a good indication on a difficult to grasp material property. **5.** I liked having all the different materials in the same size so we could easily see the difference between each material. **6.** The game was a really simple yet effective interactive demonstration. It was unique and I liked it! **7.** I really enjoyed the process of making the graph and logically thinking if it made sense.
Q8 Comments (4th yr) *[comment on one aspect of the activity you enjoyed]*	**1.** I'm glad to have had the chance to do handicrafts in class. **2.** The physicality of each test was really nice and helped my understanding of material properties, as I could physically touch or see the results. **3.** I really enjoyed how interactive it was. Honestly, all of my negative scores are just because this game isn't meant for someone at a fourth-year university level. Other than that, I think it has a lot of potential. **4.** It's generally a cool apparatus. **5.** I enjoyed that we got to perform experiments. **6.** The hands-on aspect is great. **7.** It's a fun educational game. I like that you must perform small, fun experiments to find the answer. **8.** Experimenting with different materials was enjoyable.
Q9 Comments (2nd yr) *[comment on one suggestion for improvement]*	**1.** It would be cool if there was an unknown material that we had to use the database to figure out what it was. **2.** I would prefer to compare more material properties. **3.** Would be cool if there were more materials to plot on the graph. **4.** Ideally smaller groups, so everyone can be as engaged as possible.

	5. If there was a possibility to have fewer people in the class, we could try other tests like for electrical conductivity. **6.** Maybe a bit more clarification on the reasoning behind these tests. For example, it wasn't quite clear why "scratch tests" are conducted on materials before we began this lab. **7.** Improving by finishing with an overall explanation of what each graph means and comparing it with the rest of the lab would be ideal for the in computer lab part.
Q9 Comments (4th yr) *[comment on one suggestion for improvement]*	**1.** Streamline the procedure for more predictable results. **2.** In our experience, the temperature measurement portion of the activity was somewhat inconsistent for the metal materials. **3.** I think a board game needs more incentive to "win." Maybe each student could make a prediction and earn points for being correct. That way, every time they set up a new graph, they're motivated to earn points. **4.** There should be a goal, scoring system, or some form of competition. **5.** The Newton's cradle mechanical loss jig could be much more stable. To me, this would be the most exciting activity if I were in high school. Making it more reliable would significantly enhance student engagement.

5. Dissemination of Game Materials

As stated above, all instructional materials for this game are freely available to download from the Ansys Education Resources website. When preparing the documentation for wider dissemination, two main questions were asked: (1) how do we explain this game clearly to those who are seeing the content for the first time, and (2) is there a way to create a "simple" version of this game, targeted at younger audiences (approximately ages 5-10).

To answer Question 1 and help educators implement this game, regardless of background knowledge, we introduced a Facilitator's Guide. This document covers all information needed by an instructor – from game equipment needs to detailed instructions to alternative tips for implementation. We plan on improving this guide as more user feedback is received.

To answer Question 2, we introduced two versions of the game: Simple and Advanced. The Advanced version is the same as explained above for this study, where students estimate material properties via measurements made using equipment. This version contains terminology that one would expect to see in a college-level materials science course. The Simple version can be thought of as "Touch & Feel" – taking advantage of the curiosity of young children and their wish to touch and feel everything to better understand it. The design of this version includes property estimation measurements that do not use equipment and simplified terminology in the explanations. While this leads to much less accurate experimental results, we hope this method will make discussing abstract materials science concepts easier. The same properties are introduced for both versions of the game. Figure 10 shows an example of the material property card explaining ‘density’ for both the Simple version (left) and the Advanced version (right). Note the difference in complexity of language used and topics covered. We hope to gather feedback, particularly on the Simple version of the game soon and make adjustments as needed.

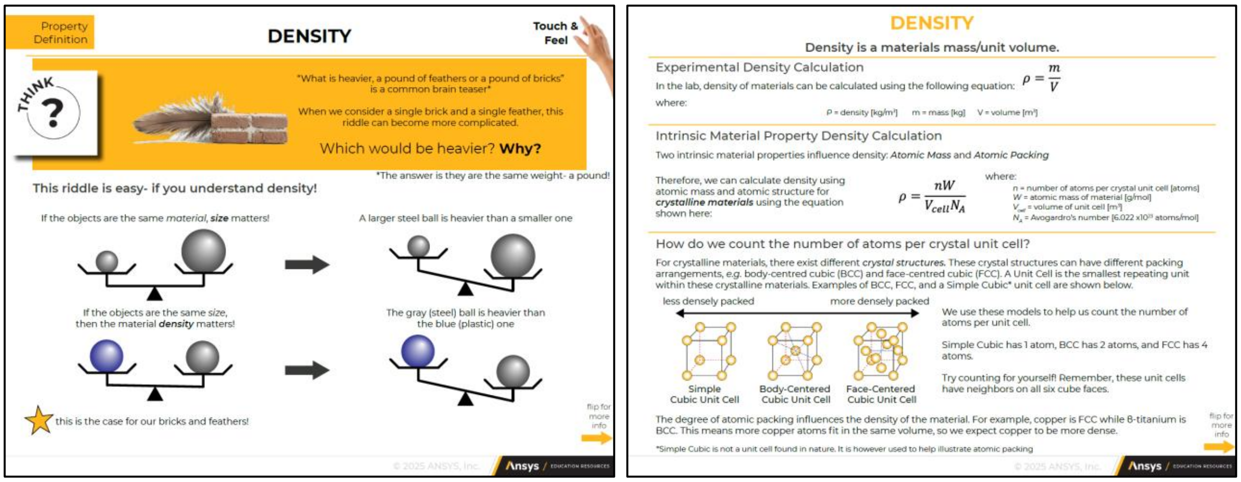

Figure 10: Material Property Cards for Density for the Simple Version (left) and Advanced version (right) of the game

6. Concluding Remarks

The Multi-Material Marbles Game has proven to be an engaging and effective educational tool for introducing materials science concepts. By allowing students to experiment with marbles made from various materials, the game enables them to measure and compare key material properties such as density, thermal conductivity, and mechanical strength. These hands-on measurements form the basis for creating Material Property Charts, which help focus the engineering design space and visually guide the materials selection process. This tactile approach makes abstract concepts more accessible, fostering a deeper understanding of materials science.

Survey results from both second-year and fourth-year students highlight the game's appeal. The second year cohort in particular found the game to be engaging, fun, and effective in helping them better understand materials science. In fact, there were suggestions to expand the game activities further to include other materials or other experimental tests. While the more advanced fourth-year students suggested it was better suited for newcomers to the field, their feedback underscored the game's ability to increase interest and understanding. In both cases, the game successfully engages students by promoting active learning and reinforcing key concepts in an interactive way. Future iterations will focus on refining the procedure and introducing incentive systems (e.g., competition) to further enhance its effectiveness.

Finally, the Multi-Material Marbles Game serves as an excellent outreach tool, sparking curiosity and generating meaningful discussion, especially among younger audiences, such as early undergraduates or high school students. The hands-on, interactive nature of the game makes it a powerful way to introduce materials science, build interest in the field, and encourage further exploration. The addition of a 'Simple' version, requiring no specialized equipment or technical jargon, will hopefully make this game accessible to even younger students. Overall, the game is a valuable educational resource that makes learning materials science more engaging and accessible to all.

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