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Effectiveness of Debugging-Design in 2D Simulations to Facilitate STEAM Learning

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Abstract: In our previous paper we discussed reports of the declining interest in STEM subjects of high school students in Malaysia and proposed a framework and methodology that uses 2D simulation application to facilitate learning physics in STEAM. In this small pilot case study, we present our hypothesis using a debugging-design approach with 2D simulation applications and the development of scaffolds and gamification for the learning environment. A preliminary experiment was conducted with middle school students to test the system's effectiveness. We present a breakdown of the student assessments and analyze the questionnaire responses. Findings indicate that although the system needs a bit more work on scaffolding features, it is effective in helping students increase their interest in STEAM and move up Bloom's Taxonomy.

Keywords: Simulations, Scaffolding, Learning-by-Design, Gamification, STEAM Education

1. Introduction

1.1 Background

This paper serves as a follow up to our previous work on using 2D simulation applications to motivate students to learn STEAM (Tembo & Lee, 2017) to address the reports of declining interest in STEM subjects among high school students in Malaysia. In this paper, the term STEM will be used when referencing other sources. Since our study will be integrating art and design with STEM subjects, the term STEAM will be used to refer to our work. In Tembo and Lee (2017), we proposed a theoretical framework developed by using a combination of Learning-by-Design (Kolodner et al, 1998, 2003) and other pedagogies along with PhET and Algodoo simulation apps to teach students Physics topics facilitated by a website with gamification features. In this paper, we fill in some gaps from the previous work-in-progress, discuss developments in the research and share results from our preliminary testing.

1.2 Objectives

The main aim of this research is to use educational technology to create a more approachable method of scaffolding students to learn and understand STEAM concepts and content and then test its effectiveness. We hypothesize that scaffolding Physics learning based on debugging and design/creation, grounded on an integration of Case-Based-Reasoning (CBR), Learning-by-Design (LBD) and Collaborative-Problem-Solving (CPS) would result in better learning performance based on Bloom's Taxonomy.

With the objective of validating the effectiveness of the proposed framework and considering the afore-mentioned problems, the objectives of this research are to:

1) propose a framework that makes learning STEAM more intriguing and less intimidating.
2) propose tools to aid students to visualise concepts and make clearer connections between the subject topics and real-world situations to give them more confidence in STEAM subjects, increase their interest in STEAM and possibly pursue it as a career.
3) develop a system using points 1) and 2) to facilitate and motivate the learning of STEAM.

4) test the hypothesis using the system developed in point 3).

This method needs to be measurable and testable to gauge if it helps them better grasp how STEAM works in the real world. Hence, after students participate in the learning activity, the quiz results are used to determine if they have a better understanding of STEAM concepts and the pre- and post-activity questionnaire findings are used to determine if:

1) their interest in STEAM has increased;
2) the system and activities eliminated their perception of how difficult STEAM is;
3) if it dispels the belief that only top students can pursue STEAM subjects.

2. Literature Review

While reviewing the physics curriculum in Malaysia, Bunyamin and Finley (2016) used a suggestion by Roehrig, Moore, Wang and Park (2012) who stated that there is a natural fit between physics and engineering at high school level. Furthermore, in a survey conducted by Wilkinson and Lancaster (2014) on 209 students, 97 were studying STEM subjects. Findings showed that technology can motivate STEM students. These studies support the decision to motivate students to take interest in STEAM using technology to teach them Physics. The type of technology to use is partly based on Mellema's (2001) physics education pedagogy where he assigned tasks, problems and quizzes via the WebAssign website and incorporated Physlet simulations of a physics phenomenon that students could interact with to help visualise the concepts and solve problems. His method of testing students at multiple stages aided students to develop Bloom's Taxonomy (Anderson & Krathwohl, 2001) progressively.

Fostering higher order thinking skills (HOTS) can be achieved by incorporating Case-Based Reasoning (CBR) with Problem Based Learning (PBL) and Learning-by-Design (LBD), a pedagogy developed by Kolodner, Crismond, Gray, Holbrook and Puntambekar (1998) and Kolodner, Camp, Crismond, Fasse, Gray, Holbrook, Puntambekar and Ryan (2003). In CBR, the cycle of retrieving, reusing, revising and retaining cases, teaches students to decompose data, recognise patterns, extract the essential information and analyse it to draw probable conclusions, which sharpens the apply and analyse skill bands. To fulfil the evaluate and create bands PBL and LBD can be applied.

The process involves the students approaching a real-world problem using the knowledge they already have and applying their acquired knowledge to build physical models that showcase their hypotheses on the topic. Similarly, we went back to technology-enhanced learning and asked students to evaluate a situation and subsequently, create 2D Simulations of their solution. Simulations are an ideal form of educational technology as they can display abstract scientific concepts that may be difficult to recreate in the real world. Rutten, Van Joolingen and Van der Veen (2012) conducted a field review of 51 publications that investigated the effects of computer simulations in science classes and reported that it generated higher learning outcomes and a better grasp of scientific concepts.

Scaffolding student progress and monitoring participation are essential to ensure each student is meeting the learning objectives. Owensby and Kolodner (2004) developed the Case Application Suite (CAS) which consists of questions, hints and examples that prompt students to collaboratively record their ideas, proposed solutions, experimental trials, results and present reports. The tools are designed to scaffold learners through iterative cycles of their PBL and LBD classroom challenge. They tested the effectiveness of CAS by comparing the capabilities of students who used the software and those who did not. Their results showed that the class that used CAS performed better at analysing and applying cases than students who did not. They were also better prepared to apply those skills in the absence of the software showing they understood the steps involved in the acquisition and transferring of HOTS.

With the adoption of self-directed online tools, a teacher may be unable to keep tabs on student engagement. Gamification can be used to enhance engagement and drive student learning. Muntean (2011) conducted a study on using the appropriate gamification techniques to raise e-learning engagement and she discovered that gamification is a combination of intrinsic and extrinsic motivation techniques. Intrinsic being the user's decision to make an action e.g. competition, and extrinsic occurring when something else influences the user to make an action e.g. ranking, point and badge system. She concluded that gamification can motivate students to study more by keeping them engaged and wanting to learn more due to the positive feedback they receive from a gamified system.

To consolidate this review, we believe the objectives of this research can be achieved by using 2D simulation technology in conjunction with a gamified website that quizzes the learner while also scaffolding them from the LOTS to HOTS on Bloom's Taxonomy. The gradual progression to HOTS will make learning STEAM less intimidating and the use of 2D simulation will help learners better grasp how theories work in the real world which in turn can give them more confidence to pursue STEAM subjects.

3. Proposed Framework and Tools

Objectives 1) and 2) have already been discussed in our previous paper. Figure 1 shows the components to be included in the STEAM Learning Framework and Table 1 summarizes the proposed structured framework following Bloom's Taxonomy. This framework will consist of a scaffolding website and a standalone 2D Simulation App where you can save 2D Simulation work files and upload them as answers to the website. The proposed 2D Application tools we selected were PhET Interactive Simulations that can be embedded into the website and Algodoo 2D Simulation App that allows the user to create and manipulate their own simulations and visualize how physics phenomena works on them. Both applications have the ideal features needed to facilitate in teaching the Form and Function topic in 7th grade Ontario Curriculum.

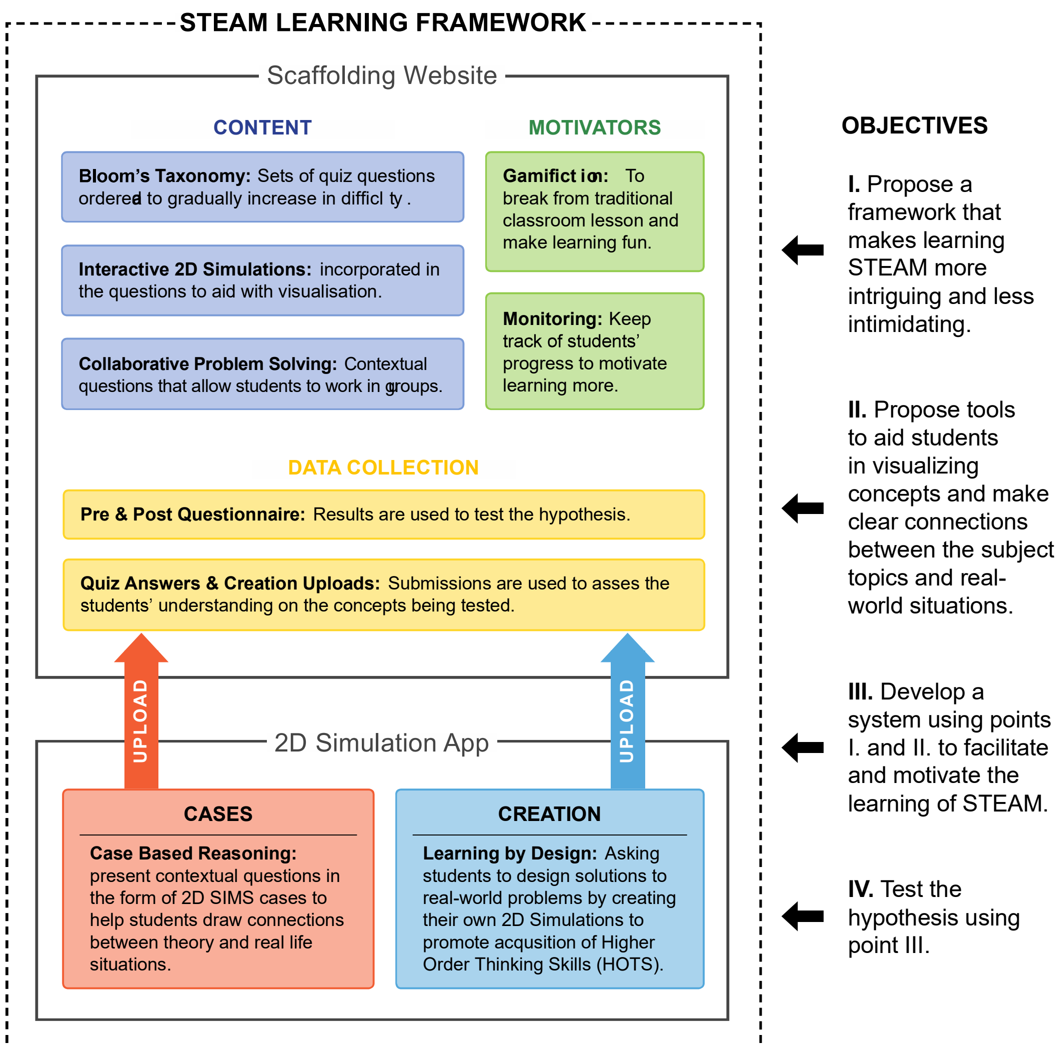


Figure 1. STEAM Learning Framework Components

Table 1. Structured framework following Bloom's Taxonomy

Level	Bloom's Taxonomy	Student Tasks
1		Conduct pre-activity questionnaire at the Debugging-design website to assess students' current STEAM interest before using the system.
2	Remember	A multiple-choice quiz on the website to help students review and gauge if they recall the basic concepts and definitions of Form & Function. Some questions are presented in simulation form to aid visualisation.
3	Understand	Students play with PhET simulations similar to the Physlets in Mellema's (2001) pedagogy and answer MCQ and short text questions that help assess if they are able to identify the concepts in use and explain how they are being used in the simulation.
4	Apply	Students are grouped heterogeneously by academic ability based on the marks for the first two activities like in Mellema's (2001) methodology and are presented with short cases of real-world problems. The questions come with Algodoo simulation case files that they need to amend by using the learnt concepts to fix the problematic simulation and upload the corrected file on to the website. There will be some short text questions on their solution to assess if they effectively connected learnt theories and applied them to the new case and demonstrate they understand its purpose.
	Analyse	
5	Evaluate	The final task is similar to Kolodner et al's (2003) Learning-by-Design where students are presented with a real-world problem and must design a bridge in Algodoo to support a car. They must brainstorm a solution and be able to justify it using Form & Function concepts they have learnt. On completion, they will upload their Algodoo simulation to the website with a write up explaining their design process and the factors to support it.
	Create	
6		Conduct post-activity questionnaire on the website to record students' STEAM interest and their experience after using the system.

4. Website Development

After establishing the structured framework and the simulation applications to be used, a scaffolding system needs to be developed. The general system architecture in Figure 2 serves as a guide of how this framework will be implemented.

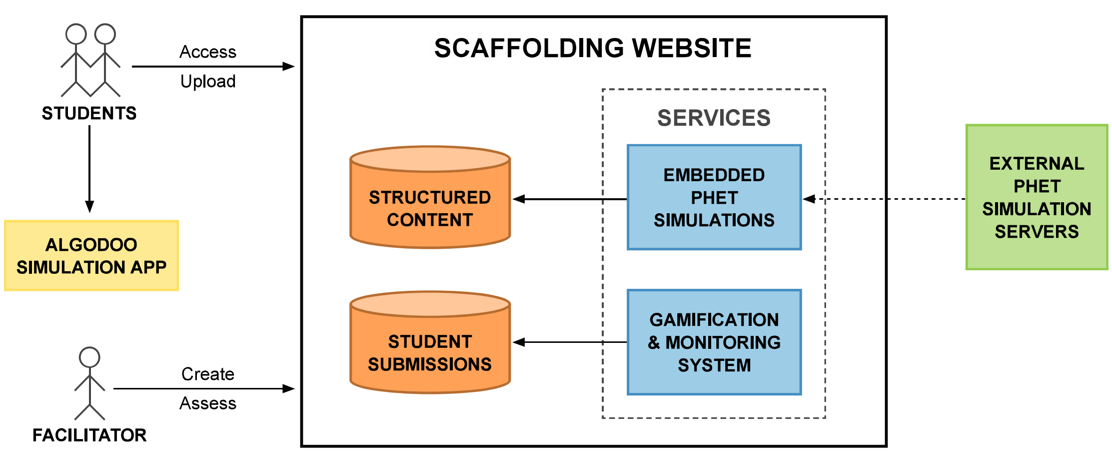


Figure 2. General System Architecture

The main users are the students and the system facilitator. The facilitator will set up structured content according to the students' syllabus and learning objectives. This content includes quiz questions, questionnaires and embedded PhET Simulations from the PhET official website. Another service the website will feature is a gamification and monitoring system which will keep track of students' progress, scores and rewards. These stats will be recorded as the students go through the activities and submit their answers and designs from the Algodoo Simulation App.

Figure 3 shows a sample page of what the website with all these features look like from the student's end.

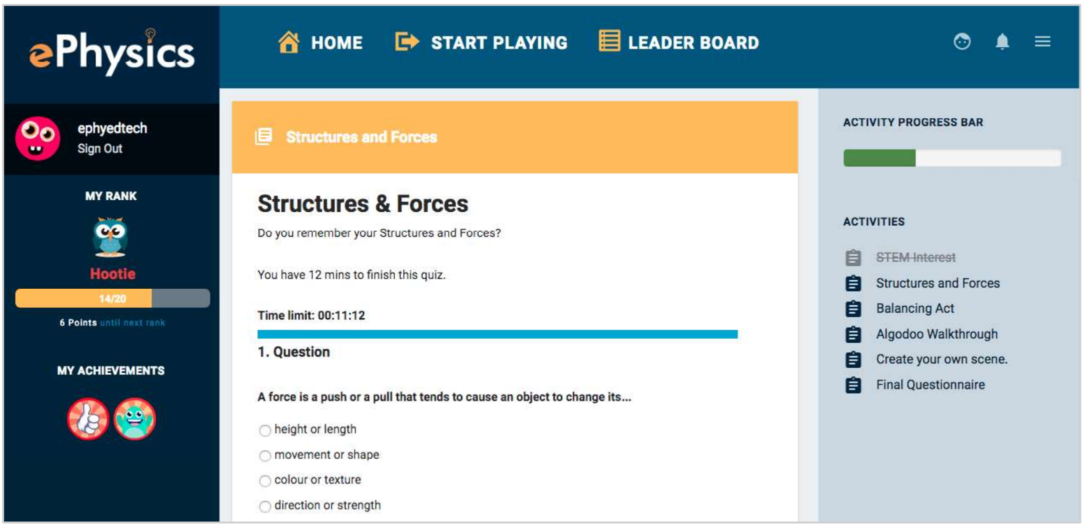


Figure 3. Quiz page of the scaffolding website with gamification features

Upon logging into a pre-created student account, the scaffolding website will guide students to work from lower order thinking skills (LOTS) to higher order thinking skills (HOTS) using game-like levels as seen in the right sidebar. Each level comes in the form of a quiz or activity that tests their skills for a corresponding Bloom's Taxonomy learning objective. Each level is locked and can only be accessed by completing the previous level. A progress bar and greyed levels keep the player updated on their progress and the levels they have left so they are motivated to complete all the tasks.

Another feature that supports engagement is the ranking, points and achievements feature on the left sidebar. With each completed level, an achievement badge will be added to their profile. Students are also awarded points which accumulate and evolve with their ranking. Students can keep an eye on their rank status as well as their classmates' on the leader board linked at the top to spark some friendly competition which hopefully will in turn drive them to complete more levels and encourage the acquisition of HOTS.

5. Preliminary Experiment

A pilot test was conducted with middle school students in the 7th Grade. This class was selected because they were currently partaking in the Ontario Curriculum STEM program. We were able to develop our activity on their Form & Function Physics topic so it integrates perfectly with their established lesson plan. We made sure our quizzes fulfilled their learning objectives making our activity a form of revision and self-assessment for the class. Students worked through 6 levels of the game and responded to the pre and post questionnaire which were Level 1 and Level 6 respectively. To be able to compare the effectiveness of the full system, only students A to E, who finished all 6 levels without skipping questions were considered. The students' answers from the tests were assessed first and then their questionnaire responses analysed.

5.1 Student Test Assessment

The first test, Level 2 was a 20-minute timed quiz on form and function comprising of 12 questions in text or image formats of **Multiple Choice** (MCQ), **Drag and Drop** (D&D) and **Fill in the Blank**

(FIB) questions. The learning objective was the ability to recall the appropriate vocabulary and be able to define shapes, structure and their components. This quiz was created to help students review and gauge if they remember basic concepts of Form & Function. The results show that all the students scored above average marks. The question breakdown shows that the question types with highest success rate were D&D questions while the FIB questions had the lowest, indicating that they are able to match definitions if provided with choices. However, recalling the appropriate vocabulary from the top of their heads without any hints was a bit challenging.

Level 3 was a PhET Simulation-based quiz called Balancing Act comprising of 10 questions in 4 formats. The questions ranged from MCQ, FIB, short text responses, rewarded by game scores. In this quiz, students played with PhET simulation objects on a see-saw and answered questions to assess if they were able to explain their ideas with the concepts and vocabulary they remember. Table 2 shows a comparison of the students' performance between Level 2 and 3.

Table 2. Level 2 & 3 Student Performance Comparison

Group	Student	Level 2	Level 3	Bloom's Taxonomy Learning Objective
1	A	83%	90%	Acquired understand skills band
	B	69%	86%	
	C	52%	69%	
2	D	66%	38%	Understanding skills *may be* weaker
	E	55%	34%	

The results show an increase in scores for students in Group 1 and a decrease for those in Group 2, indicating that they found this level a bit challenging. The short text answers showed that Group 1 could mostly identify and explain the concepts they learnt, able to recognize how distance and weight played a part in the playground scenario questions showing a good understanding of the topic. Group 2 have either problems in understanding the question, when it comes to multiple assumptions or is not very serious as the exercise is not graded. We cannot make conclusions about their level of understanding because the triangulation of data between MCQ, and their two designs and respective explanations show that there is some understanding.

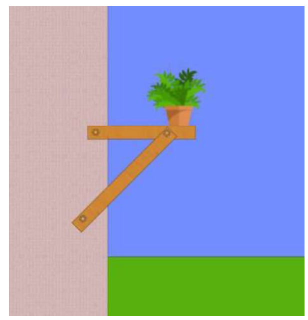
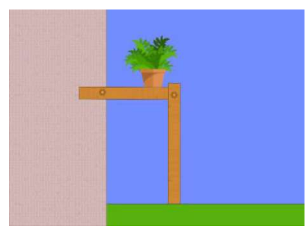
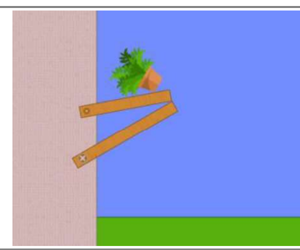
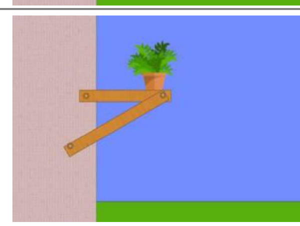
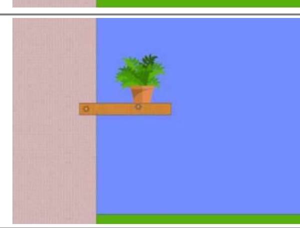
Similar to the Recall Quiz, the FIB questions had the lowest success rate, which prompts the question of whether the problem was not understanding how to apply the concepts being taught to calculate the correct answer or not understanding how to use the PhET simulation to get the values needed to answer the question. The latter concern is also raised for the game question that asked students to play level 1 game of the PhET simulation and submit a screenshot of their points. Some students were unable to take and submit a screenshot despite instructions being included in the form of an annotated screenshot, resulting in their submissions being unusable. The purpose of this pilot test is to eliminate problems caused by system or unclear instructions and make it as efficient as possible for the next round of testing so that the students' marks solely reflect their knowledge on the concept. To achieve this, clearer instructions need to be displayed before the level quiz starts. In the next version of the website we would like to add video tutorial instructions that show an example of how to play the level so as to not cause any confusion during mid-quiz. This method of scaffolding should be able to make answering questions and understanding instructions clearer and prevent execution errors.

Level 4 introduced the students to the Algodoo 2D Simulation and comprised of 6 questions. Since they had no prior experience with the app, questions 1-4 required them to complete the built-in assisted tutorials. These tutorials are interactive step-by-step guides that walk the student through learning about the application tools and how to use them. Questions 1 and 2 are fully guided however question 3 and 4 are less so and allows the students to use the skills they gained in the first few tutorials to follow instructions and answer questions.

Table 3 shows the responses they gave in questions 3, 5 and 6. Students showed good understanding of how friction works from the slides they created and were able to explain how the different materials and angles they were instructed to use altered the amount of friction in each slide.

Questions 5 and 6 had no assistance and tested the students' ability to use learnt information in new situations and draw connections between similar cases and concepts. They were asked to download an Algodoo file which had a broken shelf. Their task was to use a spare piece of wood to make the shelf strong enough to hold the flowerpot and be able to explain their solution using the vocabulary and concepts that were tested in earlier levels. Students A and D were able to draw the connection between this case and the topic of strut and compression tested in Level 2 and explain it correctly, showing good application and analysis skill acquisition. The other students used other methods to fix the shelf.

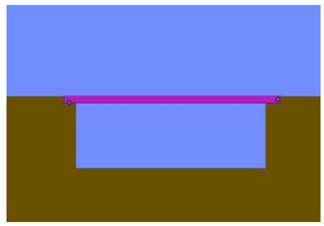
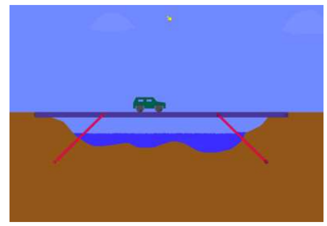
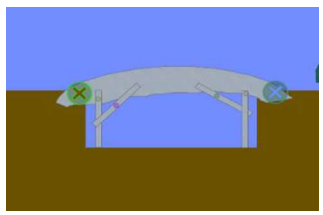
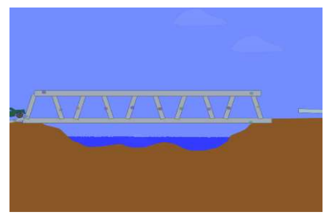
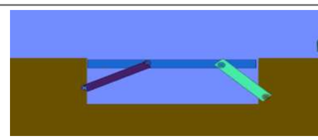
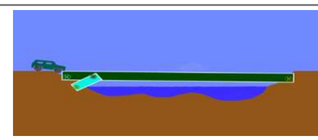
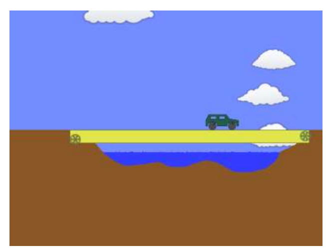
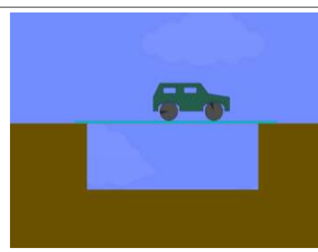
Table 3. Level 4 - Algodoo Broken shelf exercises short text answers & uploads (friction, material, strut, compression)

Student	Question 3 (how friction works)	Question 5 (fixing a broken shelf explanation)	Question 6 (fixing a broken shelf simulation upload)
A	- The box will slide faster on soft surfaces such as ice/glass. It will slide slowly when on rough textures, such as wood, because there will be more friction. - The boxes will slide faster when the angle of the plains is closer to being vertical than horizontal. - It is not the same for all planes. The texture of the plane makes a difference.	I turned the structure into a strut. When gravity pushes the pot down, the strut (diagonal piece of wood) is compressed but still keeps the horizontal piece of wood stable.	
B	- There are differences in how the box is picking up speed because of the qualities the beams are made of. - If the angle of the plain is decreased, then it will move slower. - No, it is not the same for all the plains	I used this to fix the shelf because if I add support to the side of the shelf, then it would not fall down but stay in one place	
C	- It has difference because when you have a smooth surface, it will be more faster and if you have a rough surface, it will be more slower	I put the wood under another wood so that it won't fall.	
D	- I have made a square block out of ice sliding down a glass inclined plane slope. The ice was slippery so it slid down the slope I made.	I made a strut shelf, I added a rectangular box and attached it to the original shelf it had. this shelf uses compression	
E	- Yes, there are differences cause the material of the slope has smooth or rough textures. The speed is different when the square is sliding down. - The square slide down faster	There is gravity happening in the wood.	

The fifth level is another Algodoo level, however this time the students do not have any assistance and are free to design and construct solution on their own. The students are to download

2 files; easy and hard respectively. Each file has a car positioned before a huge gap in the earth where they are supposed to build a bridge that can support the weight of the car and get it across to the other side using realistic approach. Question 1 asks them to identify the bridge they built and explain why their reasoning. Question 2 and 3 is where they will upload their creations for easy and hard bridge respectively. Table 4 below shows their answers and file submissions.

Table 4. Level 5 - Algodoo bridge design short text answers & uploads (friction, materials, strut, truss compression, arch, beam, vertical support)

Student	Question 1	Question 2	Question 3
A	I used a simple beam for the easy bridge because the load of the car isn't enough to break it. I used a strut for the hard bridge, it gives the bridge support from below so that it doesn't break.		
B	For the easy bridge, I used arch bridge which had struts supporting the bridge which was made out of steel whereas the hard bridge was a truss bridge made of steel		
C	I build an arch bridge so that the bridge will be strong enough to hold the car		
D	I used a beam and vertical supports to hold the bridge. I used the vertical support bridge for both easy and hard bridges. I used this method for my bridge because it is simple and strong.		
E	I decided to use a beam bridge and I used that because it is lighter for the car to cross the bridge.		

Students D and E used a simple beam bridge, students A and C did the same but used struts to support their bridge. Only Student B went with a more realistic approach by using steel materials to reinforce their bridges. They created a truss bridge for the harder bridge, showing exceptional application of the material they learnt compared to their peers. Student B produced the most creative solution which showed development of their HOTS as they are able to evaluate a scenario and create proficient original work for its function.

6. Results and Discussion

6.1 STEAM Interest

Before the activity started the students took a short questionnaire on their current STEAM Interest, the responses were then compared to the post activity ones in Table 5.

Table 5. Questionnaire Responses – Comparison of STEAM Interest Pre- & Post Activity

	Q1. I think STEAM is interesting.		Q2. STEAM is hard for me to understand.		Q3. I'm considering STEAM in high school.		Q4. I would consider a career in the STEAM field.		Q5. It's important for me to be good at STEAM.	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
Strongly Agree	1	2	2	2	2	2	1	2	2	2
Agree	5	4	0	0	1	2	0	1	4	3
Not Sure	1	1	1	3	3	3	5	3	1	4
Disagree	0	0	3	2	1	0	1	1	0	0
Strongly Disagree	0	0	1	0	0	0	0	0	0	0

Responses showed there was a slight increase in STEAM interest and that more students were considering taking STEAM subjects in high school. They agreed that it was important for them to be good at STEAM and more students are now considering a career in the field after playing the activity.

6.2 Feedback of the System

In the open-ended questions, the majority of students said the best part of playing this activity was building the bridge in Algodoo, followed by playing the PhET Simulation. One student specified that the best part was "Understanding real life concepts and problems that engineers may face when building structures."

When asked about their least favourite part the most common response was the friction of a sliding object question that was incorporated in the Algodoo tutorial. They voiced how *"it was hard for them to understand what to do"* and that they *"did not understand it as well as other levels."* This tutorial is built into the application and is un-editable, so I believe the best approach would be to design a custom tutorial using instructions that are as understandable as the other levels. Other than this there were no major difficulties experienced with one student saying *"I figured it out in the end!"*

When asked if learning STEAM and how to use, science, technology engineering and maths together is important? They all agreed adding:

"because people face problems that require an understanding of all the subjects."

"because those subjects are use in real life situations and help to get a job."

"if we encounter any problems in the future regarding some of these activities we can easily overcome them"

"I think it is really important if you want to be a architect in the future as you need to use math to determine if the building will withstand strong wind, earthquakes or the weight of the building structure. As it relates to each other to also understand whether or not gravity will effect it"

"These are vital subjects in our life for sure. We need to learn these subjects to boost innovation and the products of the human race. Without these topics, we wouldn't even be doing this ePhysics questionnaire now."

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From these results, we would conclude that the activities were indeed useful and helped them with STEAM learning and understanding its importance. However, more work needs to be done to help with scaffolding and to ease their difficulties with using the system.

6.3 Research Significance

Our main contribution to the education field is proposing a *framework* that will scaffold STEAM learners from Bloom's LOTS to HOTS using this aforementioned combination of learning pedagogies and applying the use of technology at every learning band of Bloom's Taxonomy. The technology consists of a scaffolding website with gamification features and *embedded* PhET Simulation and Algodoo 2D Simulation App. We will also be introducing the debugging approach by presenting students with questions that come with Algodoo simulation case files that they need to amend and debug to nurture Apply and Analyse thinking skills before they are promoted to create their simulations from scratch for Evaluate and Create skills to derive techniques which are effective based on the debugging-design framework and approach.

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