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How do engineers do that?—An interactive introduction to the engineering design process for secondary age school pupils

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Abstract

It is widely accepted that the United Kingdom (UK) needs more engineers and professionals with skills in science, technology, engineering and maths (STEM) to benefit the economy and keep up with technological change and innovation. However, the true nature of engineering and STEM careers is often misunderstood, with secondary school pupils unable to identify where engineering benefits their everyday lives. This suggests that the societal impacts of engineering are not well-defined within secondary education, causing a lack of diversity in pupils pursuing STEM careers. The authors have developed an activity that demonstrates the true problem-solving nature of engineering, and the numerous ways in which these skills can be applied to everyday life. While most practical 'design, build and test' (DBT) exercises aim to foster student engagement with STEM, this activity also emphasises how the engineering design process is a crucial tool for reaching an optimum solution. Pupils work in teams generating ideas and learning from failure, gaining a greater appreciation of how engineers work and the truly exciting nature of engineering. They achieve this by using the engineering design process to help them complete a DBT activity involving building a bridge

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from limited materials and testing how much weight it can hold. To ensure all pupils have the same opportunities for engagement, the method of delivery, activity design, key learning outcomes, discussion points, and activity relevance have been carefully considered for pupils across a range of age groups, backgrounds, and subject interests. This makes the designed activity ideal for integration into various subject lessons in secondary school classrooms to expose pupils to engineering. The authors have successfully delivered this activity during numerous outreach schemes for pupils visiting the University of Bath, especially noting pupils' engagement and enthusiasm.

Keywords: engineering education, engineering design process, engineering outreach

1. Introduction

In recent years, numerous published reports have highlighted the need to increase the number of engineers entering the UK labour market, and promote science, technology, engineering and maths (STEM) skills more widely [1–3]. Despite this, there is a distinct lack of engineering representation within the secondary school curriculum [4]. Pupils tend to misunderstand the broad societal implications of engineering and are overall poorly informed of the significant social benefits that engineering provides [5]. Female pupils in particular are less likely to agree that engineering is specifically important to their own lives, demonstrating that engineering continues to represent a source of gender stereotypes in higher education [5].

Activities that allow pupils to engage with problem-solving representative of engineering and learn about its social impact and relevance to innovation, can help them view engineering as a career choice in a more positive and achievable light [5, 6]. Raising the profile of engineering across a range of abilities and interests, as well as emphasising the human-centred, problem-solving aspects of engineering have been identified as key approaches to promote interest in engineering in young people [5, 7, 8].

Engineering is not taught as an independent subject in the majority of secondary school curricula in England, Wales and Northern Ireland [3]. Therefore, additional approaches are needed to expose pupils to engineering prior to their formal selection of subjects that may impact their ability to easily enter an academic route to engineering [9, 10]. The Big Ideas project from the Institute of Mechanical Engineers proposes that engineering be explicitly taught as part of existing lessons from a primary school level upwards, with a broader curriculum for all pupils at secondary level to foster a greater awareness and appreciation of engineering and all that it has to offer [11]. By incorporating engineering lessons into other subjects, pupils will gain a greater appreciation of all that engineering has to offer, both in a wider societal context and in their own personal lives. As qualifications in physics are required to study engineering at a college or university level, it may be particularly beneficial to target those pupils who already study physics to increase their understanding of engineering and promote careers in engineering and/or the study of engineering at college or university.

In this paper, an interactive activity is proposed to introduce engineering and the engineering design process to pupils from a broad range of backgrounds, education level and academic ability. The activity has been designed such that no prior knowledge of engineering is required. Furthermore, pupils do not need to employ any maths or physics skills to take part, although the activity can easily be extended to better suit pupils already studying these subjects.

The presented activity focuses on the '*how*' of engineering by introducing the engineering design process as a way of solving real-life problems in society and working together in a diverse team with different backgrounds and lived experiences as a method of generating a wealth of ideas and solutions.

The authors have delivered this activity as part of outreach activities to several hundred secondary school pupils visiting the University of Bath and have seen first-hand their positive engagement with the activity, particularly those pupils who were disengaged and disinterested in engineering prior to commencing the workshop.

A framework for the activity is provided, as well as the key learning objectives and questions for learners that challenge their perception of engineering and what it means to be an engineer. Alongside this is a guide for delivery in schools, particularly those without access to local universities for engagement in such engineering activities.

The activity is designed to be flexible and reflect the background of the intended audience. Those with little to no experience in maths or physics can engage with a practical, problem-solving activity, while those with existing skills in these subjects, can include aspects such as forces, free-body diagrams, and material properties.

2. The engineering design process

The engineering design process is a series of steps, independent of project scale, which provide structured guidance, allowing engineering teams to solve a wide range of problems. It provides a framework allowing different parts of the problem to be identified and facilitates the generation of a range of ideas and meaningful solution concepts. Testing proposed designs is a key part of the process, however it must be stressed that the design process does not end when one seemingly successful solution is proposed. The process is iterative and can be repeated many times over allowing for further improvements before a final design is converged upon.

The main themes from engineering design activities are teamwork, creativity, problem-solving and perhaps most importantly, reflecting on failures [12]. Design is fundamental in engineering and spans all engineering disciplines [13]. It can therefore be used to engage pupils with a wide range of interests and experiences, by emphasising the broad application of the process.

The engineering design process is summarised in figure 1. A breakdown of each step including a brief description and the key outcomes that can be presented to pupils is given in table 1.

The engineering design process as a teaching tool lends itself to a number of practical, 'design, build and test' (DBT) activities which can increase engagement in groups that do not necessarily see themselves as interested in STEM. It can also be exploited for a variety of different projects and integrated into classroom learning to teach problem-solving and teamwork skills.

This paper outlines a 'DBT' activity designed to increase engagement and challenge attitudes towards engineering by giving pupils a practical activity to complete and test in a group [14]. An example of an existing DBT activity is given below as discussed in [14].

Save-the-citizens: design a rocket capable of carrying a maximum number of people (represented in the exercise by beans). The design cannot include any commercial parts except a given motor.

The activity is designed to be enjoyable for the pupils and aims to increase their motivation, self-confidence and curiosity [14]. The novelty of this activity lies in the emphasis on problem-solving, teamwork and reflection rather than the creation of the 'best', 'winning', or most complex design. This is achieved by guiding pupils through a single iteration of the design process in a step-by-step manner.

3. Activity set-up

3.1. Task

The task is to work in pairs or small groups to build a bridge over a fixed distance using only provided materials. The problem statement is introduced early in the lesson, however pupils are instructed not to conduct any building or testing until all other stages of the engineering design process have been satisfactorily completed.

Completed bridges will be tested with the application of a central point load. For shorter lessons, or those with younger year groups, the authors suggest using the weight of water as a point load. This is a lower risk alternative to using masses and can effectively be used in rooms where space is an issue. For longer activities, or where pupils are based in rooms with enough space to ensure falling masses are not a personal safety hazard, masses can be used to apply the point load. This is particularly effective for structures that are built from stiffer materials such as pasta, which can hold masses upwards of 20 kg.

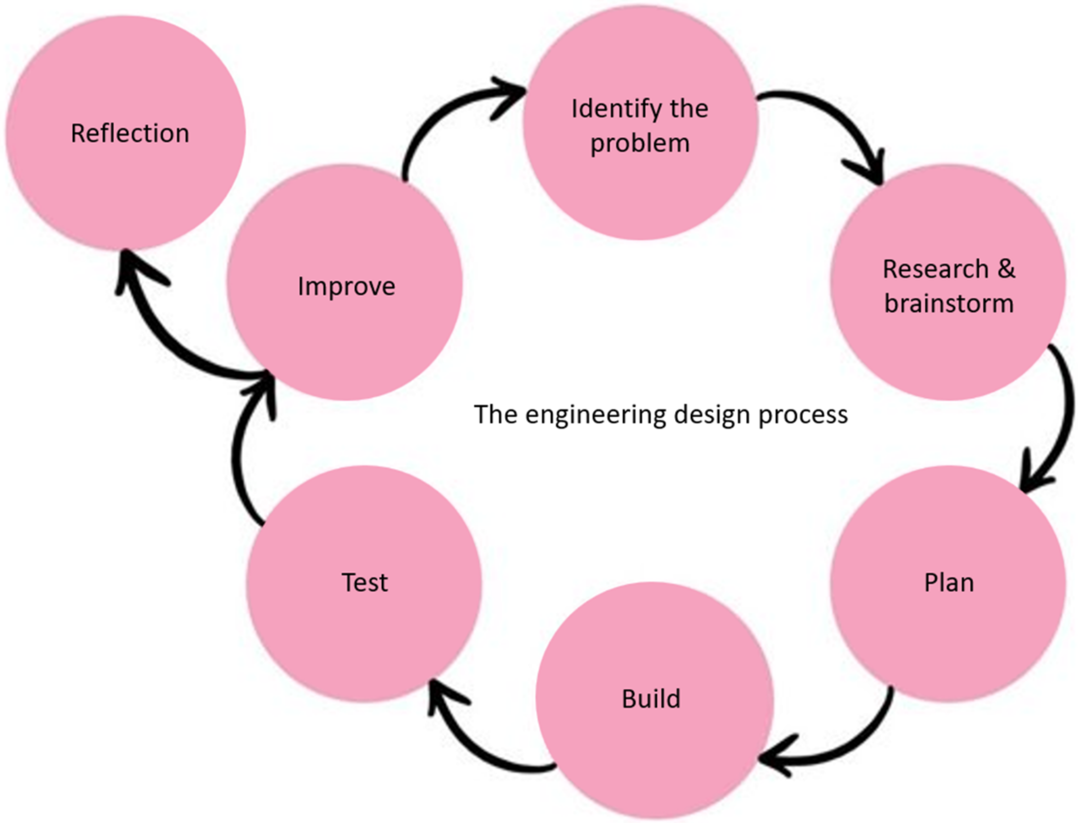


Figure 1. The engineering design process.

Where there are risks of injury or hazards, pupils can be asked to define a risk assessment, highlighting potential hazards and mitigation techniques. For simpler structures and activities using water as a point load is generally very effective and can be carried out using measuring cylinders or lightweight plastic jugs. Figure 2 shows a schematic of this task.

Pupils are given the following guidelines for their bridges, which provide enough context such that the task is clearly defined, but are open to interpretation and creative solutions:

- You need to use two blocks as the base for you bridge, and they need to be placed on the black squares (to ensure a fixed distance).
- Your bridge must join the two blocks, and can only be made of the materials you have been given.
- The strength of the bridge will be tested by placing a measuring cylinder on the middle of your bridge and filling it with water.
- The greater the volume of water your bridge can hold before it deforms such that it touches the table the more weight it can hold.
- You want to create the strongest structure using any combination of materials provided.

3.2. *Materials provided*

The activity can incorporate a variety of materials as appropriate, however table 2 gives suggested materials, as well as ways to vary the difficulty of the task.

When carrying out this activity the authors have also made use of printed handouts outlining the engineering design process, as well as including designated blank space for drawing concept ideas and planning a strategy, these are provided

Table 1. Stages of the engineering design process with key outcomes for each stage.

Stage	Description	Key outcome of stage
Identify the problem	Clearly define and describe the problem. List the constraints, requirements and end goals.	• What is the problem or need? • Why is it important to solve? • What can be changed? • What cannot be changed? • Who are you trying to help?
Research and brainstorm	Collect as many ideas as possible, everyone in the team is encouraged to give ideas. Perform some market research using general knowledge or internet resources if available. At this stage they are not expected to be fully developed but are called concepts.	A list of ideas from everyone in the team, no ideas are seen as unreasonable or 'silly' as they may spark an idea in someone else. Longer activities can include some level of market research.
Plan	Assess the list of ideas and combine multiple ideas into one concept or rank the ideas in some meaningful way to indicate the benefits/limitations of each idea.	One, fully developed, idea with accompanying sketch that will be used to solve the problem identified.
Build	Build a model or prototype of the final idea working in a team—consider roles and strengths of different team members.	A prototype model for testing to investigate if it solves the problem.
Test	Test the model using the pre-defined problem parameters. Understand what went well, and what can be improved.	Points for improvement, did the model perform as expected?
Improve	Identify a problem(s) with the existing model to initiate either another round of the engineering design process, or a reflection process to consider how the model could be redesigned for more creative solutions.	Is the design the best solution? How could it be improved? Is it worth another round of the engineering design process or should a new idea(s) be generated?
Reflection	Reflect on what you achieved and how you could improve in the future.	What went well? What could be improved? How did you work as a team? Did your team members have different skills? How did you make sure you used everyone's ideas?

in appendix A. To ensure the bridges are all of the same size, the authors usually provided a printed guide to show where to place the wooden blocks, an example is provided in appendix B.

3.3. Delivery

The following guidance is provided as a suggestion for delivering the activity (table 3). Timings and steps can be adjusted, specifically the build stage can be substantially extended, but emphasis is placed on the critical order of stages: the planning stage before the build, and the reflection stage after testing.

Table 4 provides examples of how the activity can be altered for different age groups and abilities. Examples of different materials, set up of activity and examples of student work along with the year group that conducted the activity is presented.

From table 4 it can be seen that for different age groups the materials provided can be altered to allow the pupils to create stronger and more complex designs. For younger groups typically designs can be made from paper and tape while older year groups who can safely use materials such as hot glue can do so effectively. No matter the materials provided, or the length which the bridge is expected to span, the process and learning objectives remain the same.

For those pupils who have studied various concepts in physics extensively, such as the Year 12 pupils, pupils often choose to incorporate trusses and other features into their designs,

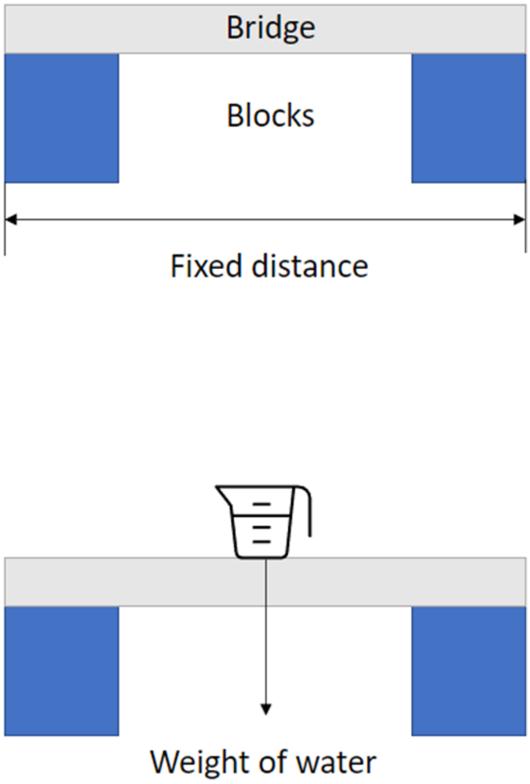


Figure 2. Schematic showing bridge building task.

Table 2. Suggested materials to be provided for task, the purpose they serve for the task and ways for educators to alter difficulty as appropriate.

Suggested material	Purpose for task	Ideas to vary activity
Wooden blocks of set size	Provide a base for bridge of known height	Increase height, width, or spanning distance. Use different shapes such as cylinders or tapered blocks.
Printed guide to show where blocks should be placed	Ensure all bridges are of set size	Include 'non-building' zones such as water, which bridges must traverse but no supports can be placed in these areas. Vary the distance between the blocks to change difficulty level.
Paper and card of pre-cut size	Provide majority of bridge structure	Change material properties, increase or decrease dimensions such that bridges must include some kind of joint or engineering challenge.
Fixing materials such as sticky tape, glue, or paperclips	Provide structure and allow for complex shapes, joints and other features to increase strength	Increase variety of fixing materials provided, change material properties such as altering type of tape or glue.

Table 3. How to conduct activity with each stage defined, as well as suggested timings for each activity.

Activity	Description	Suggested timing
What is an engineer?	Discuss perceptions and challenge stereotypes of what it means to be an engineer. This can either be in the form of a classroom discussion or presentation. Discuss the kinds of jobs engineers do, is it more than you expected?	5–10 min
Introduction to engineering design process	How do engineers solve all these different problems? How do they know they have the best solution? They work together and use the engineering design process to structure their ideas and come up with solutions. Describe the different stages and what they mean.	5 min
Introduction to task	Describe the bridge building activity, the desired outcomes and how the engineering design process can be used to achieve these goals.	2–3 min
Stage 1—identify the problem	Divide pupils into pairs or small groups to define the problem as per the engineering design process. What are the goals and requirements? What are the constraints? How will success be measured?	5 min
Stage 2—research and brainstorm and stage 3—plan	In these stages, pupils are encouraged to touch and feel the materials they can use for their bridges, but they cannot start to build. They must work together to brainstorm numerous ideas, and select one idea to take forward, or combine multiple concepts into one.	10–15 min
Stage 4—build	Build the bridge according to the final concept, following the design plan.	10–15 min
Stage 5—test	Facilitators test each design by measuring the volume of water they can hold. Pupils are encouraged to look at other groups designs and see how they perform.	10–15 min
Stage 6—improve	How did the design perform? Identify key areas for improvement? Was there anything that could have been done differently? Did the design plan deviate or was it followed exactly? Encourage pupils to consider these questions both individually and with their groups. Pupils can share their own reflections with the class if appropriate.	5–10 min
Stage 7—reflection	Did we learn anything about engineering that we did not know before? How could we use the engineering design process for different situations?	5 min

while the Year 8 pupils focus more on creating stiffer materials by combining the material properties of more than one of the provided materials. Both of these approaches are equally valuable in terms of their engineering ingenuity, representing an intuitive understanding of laminate material strength and structural mechanics and can provide ample opportunities for further learning. For example, younger pupils may find it useful to use a free body diagram to analyse the effects of applying the point load at different locations and understand where on the design they could incorporate additional support structures. Older pupils can expand on this by analysing the static equilibrium of the structure and the resultant forces in particular struts.

4. Key learning objectives

There are a number of key learning objectives/goals that have been identified during the creation of this activity. These are presented in table 5,

Table 4. Examples of how the activity can be altered using different materials and examples of student work across different year groups.

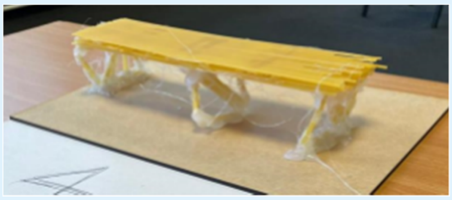
Materials provided	Joining mech-anisms provided	Year group	Bridge span	Typical loads held	Picture of student work
Paper and card	Tape and paperclips	Year 8	25 cm	<5 N	
Paper and card	Tape and paperclips	Year 8	25 cm	<5 N	
Pasta	Tape and paperclips	Year 9	25 cm	<10 N	
Pasta	Hot glue	Year 12	25 cm	100–200 N	
Pasta	Hot glue	Year 12	100 cm	100–200 N	

Table 5. Learning objectives/goals and how to measure success of the learning objective.

Objective/goal	Learning objectives and measuring success
Challenge perceptions of what it means to be an engineer by focusing more on the problem-solving aspects of the work, as well as the wide range of engineering.	Pupils are able to express how engineering affects their own lives and that of wider society.
Learn more about how engineers solve problems by utilising the engineering design process to engage in a practical activity.	Working as part of a team, pupils design, build and test a physical structure. Pupils can describe how engineers may use the same process to solve very different problems.
People from diverse backgrounds often think differently and generate different ideas—hence the need for diversity in engineering. Diverse skills and methods of thinking are all encouraged within an engineering team.	Pupils reflect upon the successes of their group and how the different team members contributed to the activity. Pupils can express their role in the activity and how this aligned with their personal strengths/interests.
The need for successful teamwork. Often during brainstorming activities team members will build upon ideas from one another and create something new.	Pupils reflect on how they approached the problem. Pupils can describe any weaknesses within their group or how they would approach teamwork differently if they were to do the activity again.
Making mistakes and constantly improving. Reflection is a key part of the engineering design process and making mistakes is a part of designing something new. That is why the engineering design process is iterative, there is always a way to improve and learn from past errors.	Pupils can quantify the success of their structure by the load that could be held. Pupils can describe any flaws in their design, or if there were any changes they would make to their structure to allow a greater load to be held.

along with the appropriate learning outcome and a suggestion for measuring the success of the learning outcome.

5. Conclusions

The work presented here describes the importance of engineering lessons and activities at all levels of secondary education, and to all pupils regardless of their interests and subjects studied. The authors have presented a practical activity that can easily be replicated and delivered in schools, integrating well with existing subjects. Methods of adapting the activity depending on the needs of the intended audience have been discussed and key learning objectives identified. The work addresses the current need to entice more pupils to consider engineering as a career choice and presents many opportunities to change pupils' views and understanding of engineering by presenting the problem-solving nature of engineering, challenging pupils to reconsider the impact of engineering on their own lives.

Data availability statement

No new data were created or analysed in this study.

Appendix A. Printed handouts

UNIVERSITY OF BATH

Engineering design process and bridge building exercise

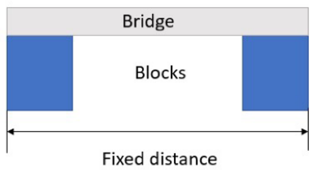
1

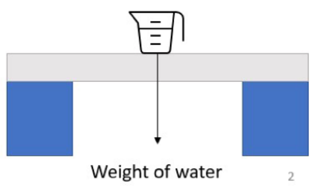
UNIVERSITY OF BATH

Your task

Your requirements for the bridge are:

1. Use two blocks for the base, placed on the black squares
2. Your bridge must join the two blocks, and you cannot build on the water
3. The strength of your bridge will be tested by the volume of water it can hold
4. You want to create the strongest bridge using any combination of the materials provided – you cannot use any of your own materials



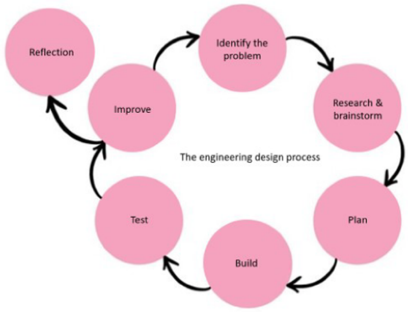


2

UNIVERSITY OF BATH

The engineering design process

1. Identify the problem. Clearly define what you are trying to do, what is the problem or need? Why is it important to solve? Does the solution already exist?
2. Research and brainstorm. Work with your teammates to think of as many ideas as possible, don't worry if they are feasible or not, just get them down on paper!
3. Plan. Look over your ideas and take the best one forward, which ones meets the requirements the best?
4. Build. Build a model or prototype of your idea
5. Test. Test your model, does it perform as you expected?
6. Improve. You're not finished yet! Can you improve your solution? How would you do that?
7. Reflection. How well did you do? Was there anything you would have done differently? How did you work as a team?



3

UNIVERSITY OF BATH

The engineering design process

1 – Identify the problem

The problem we are trying to solve is:

4

UNIVERSITY OF BATH

The engineering design process

2 – Research and brainstorm

Our ideas so far:

5

UNIVERSITY OF BATH

The engineering design process

3 – Plan

The idea we are going to take forward is:

6

UNIVERSITY OF BATH

The engineering design process

5 – Test

Our bridge could hold ____ ml of water

Extension

- How much could the bridge hold in kg?
- 1ml is 1×10^{-6} m^3
- The density of water is 1000 kg/m^3
- Mass (kg) = density (kg/m^3) x volume (m^3)
- Our bridge could hold ____ kg

7

UNIVERSITY OF BATH

The engineering design process

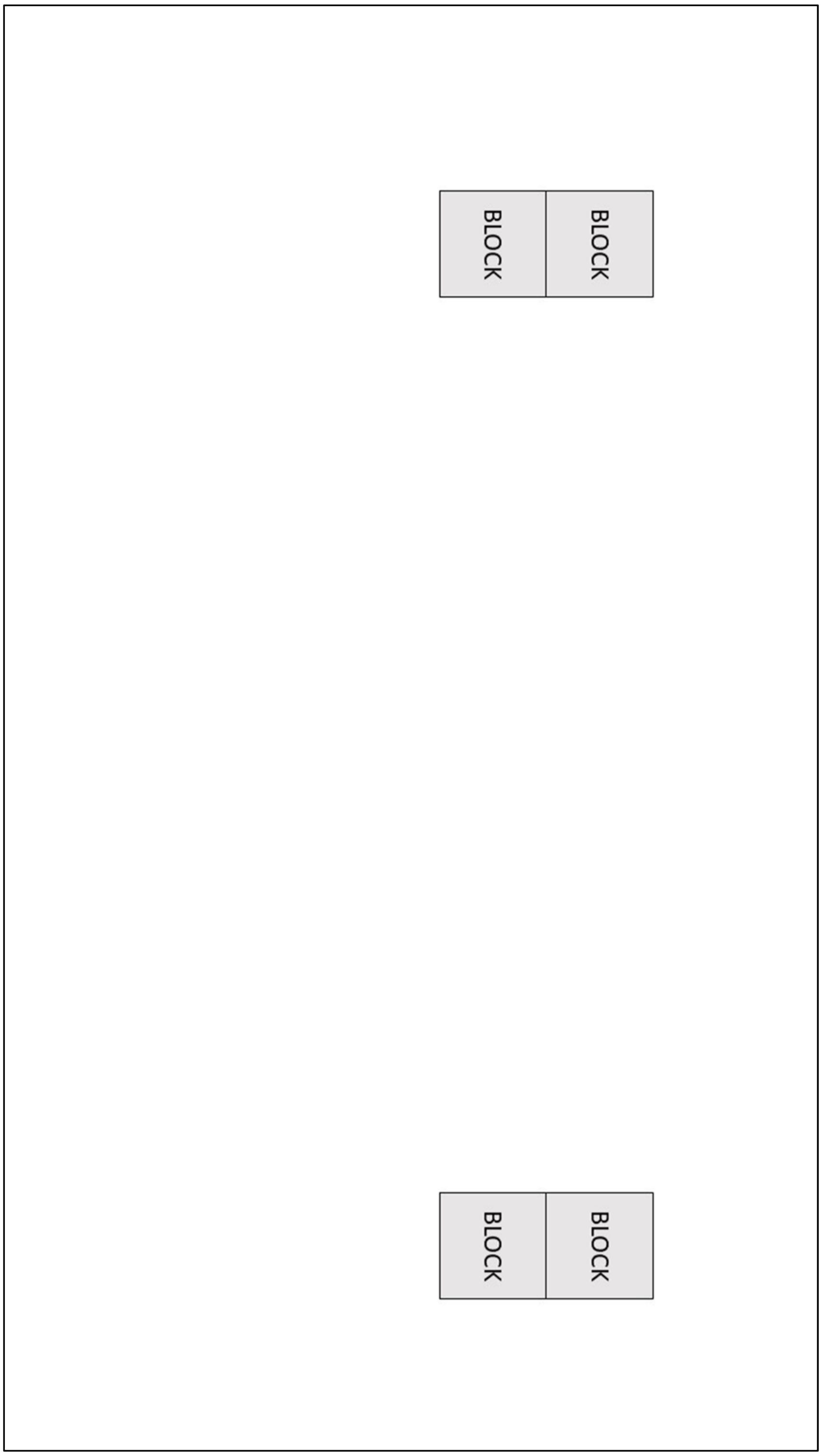
6 – Improve

If we done this activity again we would change:

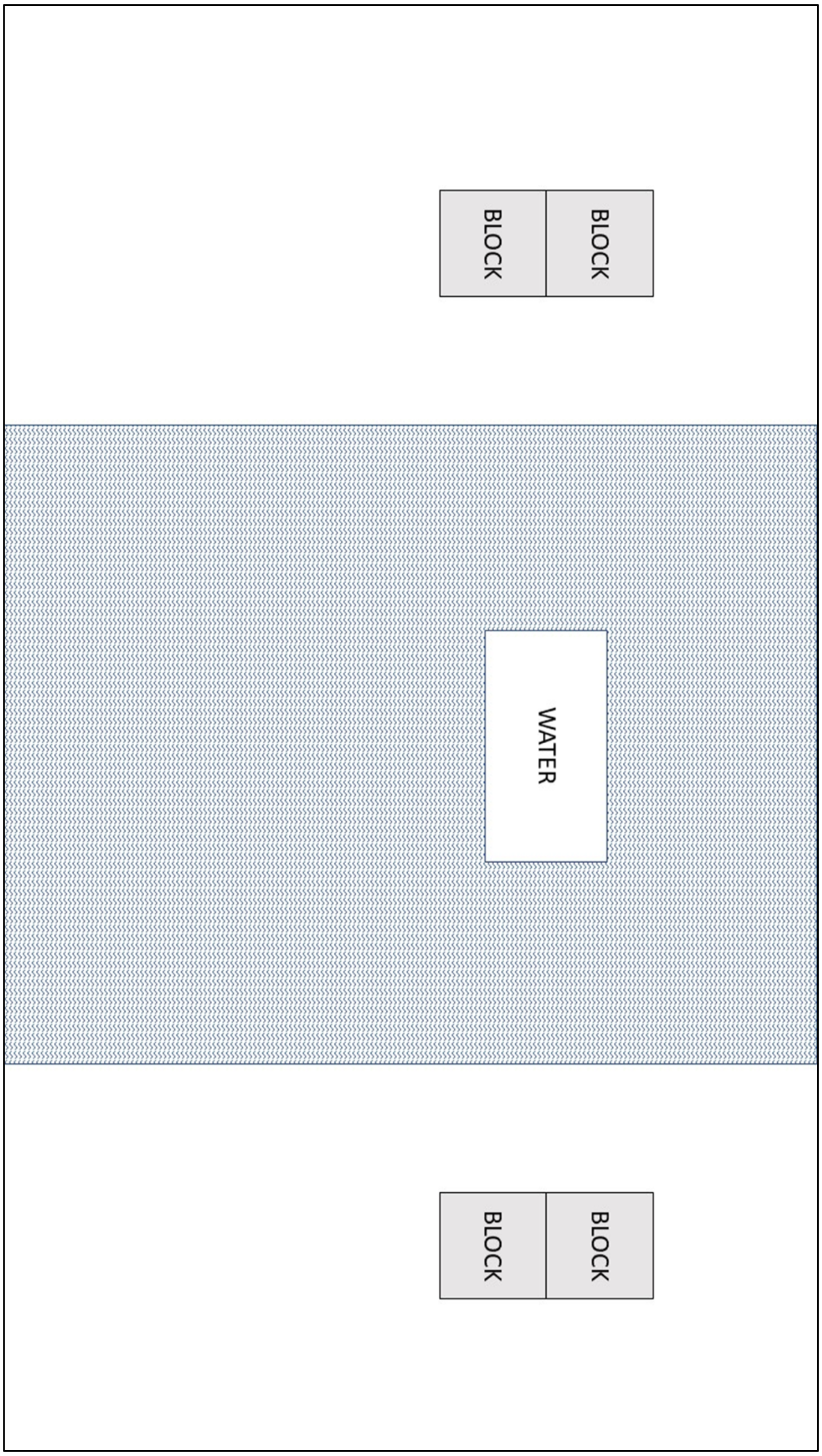
8

Appendix B. Guide for building a bridge of set distance

Easier guide (can build support structures across entire bridge span):



More challenging guide (no support structures can be built in the water):



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Samantha Hayward is a Mechanical Engineering PhD researcher at the University of Bath, UK. She is passionate about promoting STEM careers to pupils from diverse backgrounds and has been involved in programs bringing engineering to schools. Having discovered Engineering unexpectedly at a university open day while at an all-girls high school, she decided to pursue it. Having never been made aware by guidance councillors or student advisors that Engineering was even an option, she has a specific interest in promoting STEM careers to women.