Exploring Empirical Modelling for use in Education Technology

Third Year Project

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May 11th 2021

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Chapter 1

Abstract

This project explores the potential of Empirical Modelling to create educational resources that can improve the provision of education to determine whether the paradigm proves promising enough for further research. It uses existing research into educational theories, techniques, and principles to develop an understanding of the features that constitute an effective educational resource. Then, it explains the nature of Empirical Modelling and the concepts that it employs in its philosophy. These activities are combined to demonstrate the theoretical suitability of Empirical Modelling for the task of developing good educational materials. Finally, educational resources are built in the Empirical Modelling paradigm using Construit!, a development environment for modelling. These educational materials are analysed to demonstrate their properties and how they may be able to benefit teachers and students. The report concludes that the models that result from Empirical Modelling have promising properties with respect to education, and that further research is warranted to determine how Empirical Modelling techniques could be beneficial in the classroom.

Keywords: Empirical Modelling, Constructivism, Educational Technology, Learning Sciences, Construit!

Chapter 2

Introduction

2.1 Topic Introduction

Education is a fundamental element of modern society. From their first encounter at a young age through to continuing vocational training, millions of people depend on the educational system throughout their lives. They rely on an effective system of education to develop the skills and understanding required to function and pursue their interests in the complicated modern world. As a result, there is persistent interest in refining educational tools and methodologies for optimal learning.

Building effective educational institutions is the subject of intense research and refinement. The learning sciences is the academic field that developed to perform this research, using ideas and evidence from a wide range of fields to guide the construction of effective learning materials. The work of the learning sciences has been ongoing for a century since its inception, with research adapting itself to the educational goals of a society and making use of the psychological understanding and technological capabilities available to meet them[1]. One of the most topical lines of inquiry is the potential of technology to support educational activity.

The role of technology has been highlighted recently by the Covid-19 pandemic. To reduce the spread of disease, restrictions on physical meetings were imposed that made traditional classroom education nearly impossible [2]. Instead, lessons across the country were delivered online, making use of teleconferencing technologies to ensure that the schooling of children and young adults was minimally affected. This would not have been possible without recent technological advancements, which highlights the increasingly important role of technology in education provision. There is good reason to be optimistic about the benefits of a technological approach.

Technology has driven advancement in many industries – improving the efficiency, quality, and safety with which tasks can be performed. The success of technology in revolutionising other industries has encouraged the development of technology to assist teachers in their work. There have been many attempts to create educational software to assist in all aspects of the educational process. This includes a broad range of applications such as electronic flashcards, administrative and organisational systems, and presentation software. Ongoing research into education is constantly producing new ideas and evidence. Consequently, there are always new approaches to the design and implementation of educational resources to be explored and analysed.

This paper will consider one such candidate, a promising modelling paradigm called 'Empirical Modelling'. Empirical Modelling is principally concerned with user sense making and its methods are aimed at supporting the user as they use their experiences to reason about a system. This project is based on the intuition that these properties of Empirical Modelling will make it an effective educational tool, since guiding student understanding of the subject area is fundamental to the learning process. The activities described in this report are aimed at exploring this intuition, ultimately building an argument for the strengths and limitations of Empirical Modelling as an educational paradigm and discussing potential next steps for its use as a basis for new learning tools. This understanding of strengths and weaknesses can be used to inform whether future research should be directed towards Empirical Modelling for education. To achieve these goals, there are three main areas of exploration contained within this paper:

The first is a consideration of current educational theory to determine what features and properties are necessary for educational material to be effective. Secondly, the philosophy, principles, and techniques of Empirical Modelling will be analysed to determine the theoretical suitability of the paradigm to create tools that meet the identified requirements. Finally, there will be an attempt to move beyond theoretical analysis. Construit!, a development environment based on Empirical Modelling, will be used to create some educational materials with focus on embodying good principles according to educational theory. These materials will be concrete examples of Empirical Modelling resources that can be analysed to determine what unique benefits Empirical Modelling may be able to offer. This analysis can help determine whether it is beneficial to continue research into and development of educational tools based on Empirical Modelling.

The hypothesis of this paper is that there are significant conceptual similarities between Empirical Modelling and modern educational philosophies that make Empirical Modelling a promising approach for the development of new educational tools. Additionally, the models that a student might create using Empirical Modelling techniques have properties that are well aligned with modern educational design principles. These attributes could encourage further research into Empirical Modelling as an educational philosophy.

2.2 Background

Empirical Modelling and educational theory both have extensive histories of research. In the case of empirical modelling, there are decades of papers, research reports, and projects available online. Education has an even longer history, with millennia of study stretching back to the ancient Greeks [3]. The relevant aspects of this research will be discussed in detail during this report and so are not reproduced here. It is important to mention, however, that this is not the first-time empirical modelling has been studied in the context of education. There have been papers published in the past that address the potential of Empirical Modelling to be a new educational paradigm. For example, a recent paper from a constructivism conference in Bangkok discusses how Empirical Modelling tools might be introduced to the classroom "as an alternative to procedural or object-oriented constructionist environments"[4, p. 42]. There has also been some experimentation with the use of Empirical Modelling tools in a classroom to gather feedback, such as in a secondary-school mathematics class in Thailand [5]. These studies are valuable sources for this report, but they do not imply that this project is redundant.

This report differs from previous studies in its extent. Previous studies tend to be largely theoretical, or limited in the situations they consider, whereas this project incorporates a wide range of activities. The depth of this report, building from theoretical roots through to practical projects, makes it one of the most comprehensive collections of thought on the topic of applying Empirical Modelling to educational practice.

2.3 Motivation

There are many reasons to research promising educational techniques. Strengthening the education system has myriad benefits for both an individual and a society and developing tools and methods to improve provision is a key method of doing so. A discussion of these benefits demonstrates the value of continued research into educational tools.

One such benefit is that a higher level of personal education correlates with improved career outcomes, using metrics such as salary and unemployment rate. According to a 2020 analysis by the OECD, in the UK, the group which leaves education before upper secondary level has an employment rate of 65%, which jumps to 81% for the group which does complete this level. The employment rate then continues to rise with higher levels of education, reaching 87% for those with a bachelor's degree [6]. Furthermore, across OECD countries, holders of a bachelor's degree have an earning advantage of 43% over those with an upper-secondary education [7]. This demonstrates that access to good educational facilities can improve personal career success.

The profile of skills required by a population changes over time as its society and technology develop; education is an important tool for adapting to these changes. As new technologies emerge, training and teaching are essential in order to develop a workforce that has the skills and knowledge required to adapt. The OECD recognises there is a shortage of skills in a report that focuses on five countries: Spain, Italy, France, South Africa, and the United Kingdom. In particular, knowledge in areas such as computing, engineering, and mathematics are most lacking, alongside skills such as deductive reasoning and leadership [8]. Education is a major component of the OECD's plan to overcome the shortage, with policies that encourage vocational training, lifelong learning, and additional funding for students [8]. This demonstrates the importance of education for maintaining a workforce that is resilient to technological changes.

The above examples illustrate the value of an effective educational system - it allows a society to fill important, skilled roles. This implies that it is useful to consider approaches to optimize the approach to education and develop resources to support academic efforts. Furthermore, there is an expectation that technology will form an important aspect of these efforts in the future.

One area of the educational system where the emergence of technology has had a significant impact is distance learning. Distance learning was previously a small element of the education system due to challenges associated with geographical distance from an institution that were difficult to overcome – generally requiring an education consisting of mostly individual work [9]. Then, telecommunications technology revolutionised the industry by facilitating traditional, teacher-led instruction without regard to geographical constraints. Nowadays, online learning represents a major component of the education machine. In the United States, the National Centre for Education Statistics (NCES) found that 6,932,074 students studying at post-secondary institutions had at least some of their course conducted online [10]. This demonstrates the power of technology to improve access to education.

Another improvement to accessibility offered by technology is the ability to view materials asynchronously. In a physical classroom, instruction must be delivered at a specified time, at which the teacher and every student must be simultaneously available. This can be a significant limitation, particularly for adult learners who likely have external commitments and time constraints [11]. Technology brings the opportunity to circumvent this restriction, by allowing instruction to be recorded for viewing at any time.

Additionally, technology allows a wide variety of material, presented by some of the most accomplished instructors in the field, to be openly available around the world. There has been a proliferation of websites such as Khan Academy [12] that allow users to access a broad range of educational content without needing to register formally with an academic institution. Technology has made it easier and cheaper than ever before for anybody to access high-quality learning resources.

2.4 Methodology

This report explores the potential for a specific modelling paradigm, Empirical Modelling, to be used to support education. A key activity is to research and review the conceptual relationships between Empirical Modelling and prevailing educational theory. As part of this approach, the project includes both theoretical and practical components. The first stage of analysis will involve reviewing literature in the field of education to establish the practices that make for effective teaching and learning. Next, the aims, features, and philosophy of Empirical Modelling will be examined, allowing for an analysis of the conceptual similarities of Empirical Modelling to education. The ideas gained from contemporary theory will then guide the practical component of the report.

There are several tools that have been created to support the construction of empirical models, such as Construit!. Construit! will be used to build models, called construals, that demonstrate how the theory discussed in previous sections can be applied in practice to create educational tools. These tools and the experience gained through their construction can be analysed to determine the advantages and disadvantages of the Empirical Modelling approach to the building of educational resources.

Finally, there will be a summary of the limitations of Empirical Modelling for use in education, and the potential obstacles to implementing it. The theoretical and practical areas of the project can be used as evidence for the limitations of the project. It is to be expected that there are obstacles to be overcome for the Empirical Modelling approach to see widespread usage.

2.5 Aims

The aims of the project were outlined at the beginning to guide how work progressed. Now, they can be used to evaluate what the project achieved. There are two types of aim, core and stretch, with core aims being necessary to complete and stretch aims to be done if permitted by time constraints. The project proposal described the aims as follows:

2.5.1 Theory

1. Review Empirical Modelling literature to establish a solid understanding of EM philosophy and technique. (Core)
2. Review literature on the topic of education, particularly online education,with a view to establishing what makes for a valuable instance of education technology. (Core)
3. Compare Empirical modelling to these benchmarks, observing advantages

and disadvantages. (Core)

4. Examine alternative forms of interactive, online learning resources. (Stretch)
5. Compare EM to these other approaches. This will require extensive understanding of EM and CONSTRUIT! and so should not be attempted until significant practical experience has been obtained. (Stretch)

2.5.2 Practical

All practical work will involve the CONSTRUIT! environment.

1. Using existing construals to explore their topic without intending to modify them. (Core)
2. Modify the functionality of an existing construal to adapt it for my understanding of the topic. (Core)
3. Produce a new construal on a topic in my area of knowledge. (Core)
4. Critique the CONSTRUIT! language and environment, examining it for strong features and potential improvements. (Stretch)
5. Demonstrate the created construit to students, and potentially lecturers, for feedback. (Stretch)

Chapter 3

Theory

3.1 Introduction

To explore the potential of empirical modelling for helping to educate students, it is important to ground discussion in a foundation of educational theory. The overall aim for this section is to establish the principles that make for effective learning resources.

Determining how best to provide education involves consideration of many different factors that range from abstract, philosophical concerns to the visual design of materials. It is necessary to delve into this research to develop a strong understanding of how empirical modelling might fit into the broader educational landscape, the nature of the contribution it can make, and how building effective models might be approached. Additionally, understanding the criticisms of educational paradigms may lead to demonstrating that Empirical Modelling can ameliorate these concerns.

3.2 Learning Sciences

By the 20th century, the need for a structured approach to education was clear. When formalised schooling developed in the 18th century, it was based on commonsense assumptions rather than formal scientific study. Consequently, there was doubt about the effectiveness of its methods[1].

As a prerequisite for reasoning about the value of a particular educational technique or technology, it is necessary to refer to the best available analysis and knowledge concerning effective teaching methodologies. Without a well-founded understanding of how students learn, any attempt to produce tools to support that learning will be making assumptions about the best approach and are therefore unlikely to be optimal. Fortunately, there exists an extensive body of research about how best to facilitate learning, codified in an academic field known as the learning sciences.

The learning sciences is a field of study dedicated to a wide variety of learning-related activities, including “curricula, software, teaching practices, and social and interactional patterns” [1, p. 21]. The learning sciences are distinguished from other learning-related fields in that they are concerned with “bridging research and practice”[1, p. 21]. This makes them particularly valuable in the context of educational technology since they are interested in converting a solid theoretical foundation into practical tools, which is also the aim of a designer of educational technology.

There are many approaches that have been suggested for teaching practice, with different strengths and weaknesses. These approaches will be referred to as educational paradigms. Each paradigm is based on an epistemology, a philosophical position concerning the nature of knowledge. This epistemology then guides the types of learning activities that constitute the paradigm. An understanding of these activities and the reasoning behind them provides insight into how Empirical Modelling can be designed to support the paradigm.

This report focuses on two educational paradigms, chosen due to their prominence in the articles upon which this section is based. These paradigms are instructionism and constructivism.

3.3 Educational Paradigms

3.3.1 Instructionism

Description

Instructionism has been a popular educational paradigm since the emergence of modern schooling. It is so prevalent that it is sometimes referred to as the standard model. Instructionism is founded on a common epistemological viewpoint that has general appeal - that there exists a concrete, external world – about which objective facts can be known [13]. This worldview results in a set of beliefs that define instructionist practice.

An important feature of instructionism is that ’correctness’ is a well-defined, objective concept. The accuracy of a belief can be derived from how faithfully it describes the real world. The aim of an instructionist education is, therefore, to ensure that the student is familiar with these prescribed facts and able to use them in an appropriate way [1]. With this philosophy of knowledge defined, there are clear conclusions to be reached about the types of educational activity that support an instructionist approach.

Instructionism allows for a highly structured, prescribed learning syllabus. The assumption that the universe is objective and knowable implies that knowledge and procedures can be universally true and therefore applicable to all students. Students can be taught the knowledge and procedures most likely to be correct given current understanding of the external world, then use these as the basis for a single syllabus that is taught to all students [14].

Instructionist epistemology leads to activities that are teacher-led. The teacher is viewed as being in possession of all the facts and procedures that students are required to learn, therefore, the goal is for the teacher to convey this information with the greatest efficiency. The student is viewed as a passive recipient of the knowledge that the teacher transmits. When considering how to improve quality, the focus is placed on the teacher's communication and organisation [14]

With respect to making educational tools in the instructionist style, the traditional approach has been to create instructional programs, that take the role of a teacher while inviting the student to interact with the program. This interaction often takes the form of answering questions posed by the computer, then having the answers verified automatically, often with some graphical reward for correct answers. This format is in keeping with the behaviourist origins of instructionism [15].

Criticism

Despite the widespread usage of instructionism as an educational paradigm, it is not without criticism.

Ernst von Glasersfeld has argued that instructionist methods are too closely related to behaviourism. He suggests that a behavioural approach to learning misses the "distinction between training and teaching" [13, p. 1], causing students to be able to accurately answer questions of a familiar form, but lack any understanding of the deeper "conceptual relationships" [13, p. 2], required to extend the learned material to new situations. He concludes that a behavioural approach is insufficient because competence in a subject cannot be achieved through repetition alone, instead, ideas must be internalized and conceived within the student's own mind. Instructionism fails this test because it causes students to associate a question with a given procedure for determining the correct answer, while not guaranteeing an understanding of the conceptual ideas and relations that are important for true mastery of the material.

There is another concern with instructionism specifically in combination with technology. A key benefit of technology is its ability to automate tasks, but this is not inherently beneficial to education. In a paper that was published in 2007, Albirini asserts that educational technology has failed to show considerable benefits to the field despite significant financial resources being allocated to it [16].

From a modern perspective, the claim is questionable. As demonstrated during the project motivation, there are concrete examples of technology being an instrumental factor in improving the education system, particularly in the area of accessibility. However, Albirini makes a compelling argument for a paradigmatic conflict between instructionism and educational technology used as part of the student sense-making process. He explains that as enthusiasm for incorporating technology into education grew, it was mostly directed towards improving existing teaching practice rather than inventing new methods that made full use of the computerised medium. As such, technology has served to reinforce instructionism rather than expand it. This is problematic due to the irreconcilable differences in the assumptions made by technology and those made by instructionism. Computers have the power to ”democratize learning” and ”obliterate the stringent structure of the classroom” [16, p. 231], whereas instructionism is founded upon teacher control, a well-defined hierarchy and rigorously structured learning activities. These fundamental conflicts severely restrict the power of technology under instructionism, and encourage the use of other paradigms.

3.3.2 Constructivism

Description

Constructivism is an alternative approach to learning that has some popularity among learning science researchers [1]. It represents a collection of beliefs that are united under a similar broad epistemology. Perhaps the most impactful of these philosophies is radical constructivism.

Radical constructivism is an alternative educational philosophy, named after the ’radical’ nature of its break from the traditional view of knowledge [17]. It is based on an epistemology that rivals objectivism, called scepticism [14]. Scepticism suggests that the existence of an external world can never be proven since any proof would require some way to interact with that world, thereby assuming its existence. In this way, scepticism is diametrically opposed to the governing assumption of instructionism, that there exists an objective external world [13]. Education is therefore aimed at helping a student to make sense of their experiential world. This philosophical foundation has significant implications for any educational system that is built on it.

Without an external world to derive knowledge from, constructivism asserts that humans base their understanding on their experiential world instead. In this way, rather than consisting of facts about objective reality, knowledge is an organisation of a person's observations into concepts and actions that they perceive as an effective model for explaining their experiential world. As someone gains new experience that contradicts their current understanding, they adapt their conceptual models to better explain their expanded experiential world [13]. Human learning is therefore an active process of constructing meaningful relationships between experiences and observations. Since individuals have a unique set of experiences to build their conceptual frameworks, the knowledge they build is personal and subjective.

Since there is no objective reality from a sceptic's perspective, there is also no objective truth. Without an external world to compare understanding to, the concept of error is largely incompatible with radical constructivism. The 'accuracy' of a belief can only be evaluated in the context of an individual's experiential world. To account for this nuance, sceptics introduce a more suitable metric, viability [13].

Viability is an alternative measure of the 'correctness' of knowledge. It differs from the instructionist view of truth because it is adapted to a subjective reality. From the perspective of an individual, a model is deemed viable if it reliably explains all their observations within their experiential world. The experienced world is not fixed, and so agent understanding must be adaptable - there is no guarantee that a viable model will remain so indefinitely. Additionally, an idea being viable within one person's experience does not imply that it is viable within someone else's [13]. The aim of a constructivist education is, therefore, to aid the student in constructing viable models within the subject domain and determining relationships between them. There is some debate about how strictly to treat the concept of viability.

Radical constructivism takes the concept of viability to an extreme. It posits that viability must be evaluated on a strictly individual level. This does not require resorting to solipsism, the belief that nothing exists outside an agent's own mind. Instead, radical constructivists acknowledge that there is no way to prove anything about the external world [13]. This epistemological position has implications for how constructivist education should be delivered.

Firstly, constructivist education is student focused. The goal being to build upon the student's current knowledge and understanding to produce models means that the student is necessarily the central figure, with the teacher occupying a supporting role. This is due to the constructivist assumption that a student's world is uniquely individual and that all learning is affected by their preconceptions. Since the student is the only person who can access their experiential world, they must guide sense-making activity. The personal nature of an experiential world and how it affects viability has further implications for constructivist sense-making [14].

Constructivist education is an individual experience that must be tailored for each student because the models of thinking that prove viable can differ between learners. The aim is for each student to produce viable models of the subject domain, but there is no guarantee that a model that is viable in one student's experiential world will also be viable in another. Thus, the journey of building a viable model is unique to each student and the educational activities that form the journey must be unique as well [17].

Evidence

As an established educational paradigm, constructivism has been tested in schools with mixed success. These experiments provide insight into the potential of constructivism to improve student outcomes and possible obstacles to its implementation.

A study conducted in Kenya to determine the effect a constructivist education might have on attainment in biology for secondary school students found evidence of a positive impact [18]. The study shows that students responded positively to the constructivist methods that were used in the study and that there was measurable improvement in learning outcomes. This demonstrates that constructivism has potential as an education paradigm that can compete with instructionism and is therefore worthy of further exploration. The study also found insight into the difficulties that might be encountered with incorporating constructivism into classrooms.

The study found that some teachers are sceptical about constructivism's suitability for teaching as well as concerns about the allocation of resources needed to support the approach. While a plurality of teachers strongly agreed that constructivism led to higher student achievement, 48.4% thought that they could not easily be applied in a classroom setting and 46.6% did not enjoy its use. Furthermore, 68% thought that their schools did not support constructivism as a pedagogical approach with enhanced learning. These reservations imply the need to build tools that support a constructivist teaching style that are accessible, have a low resource cost, and that teachers feel comfortable using in their classrooms if the approach is to be viable in the future[18].

Additionally, a study was conducted in Namibia to determine whether the use of assistive technology tools that follow a constructivist approach would benefit the mathematics education of deaf students in grade 3 [19]. The study was an introductory exploration into how constructivist education could be applied in this context and so was limited in scope; it involved a small sample size of students from a single school. The results of the study were mixed.

On one hand, it concludes that use of constructivist assistive technology "may have had a positive effect on the multiplication and division achievement of the learners". Furthermore, the teacher assessments of the technology were generally positive, including observations of behaviour such as "collaborating", "cooperating", and "exploring" [19]. However, the small scope of the study and the fact that no benefit was observed for addition and subtraction mean that the evidence is not definitive that constructivist assistive technology is suitable for widespread adoption. Additionally, the study was only concerned with establishing a link in the sample itself, and so does not claim that the results can be generalized to a wider context. Nonetheless, it does suggest that constructivist educational technology is worth further study.

Criticism

A constructivist approach is hard to assess since there is no objective notion of correctness. Particularly in radical constructivism, understanding can only be deemed viable in the context of a student's individual world, which is only accessible by them. As such, no agent external to the user is well-placed to judge whether an answer is "correct". In this area, a branch of constructivism called social constructivism may be more effective. Social constructivism is similar to radical constructivism, except it takes a less strict view of viability. Social constructivism suggests that a model's viability can be evaluated in the context of a society rather than an individual. From this perspective, an idea should be accepted if it is viable in the experiential worlds of most of a society's members. Social constructivism makes assessment more viable from a philosophical perspective because it is hard to reach agreement without the assumption that there is some correlation between the viability of an individual's viewpoint and the viewpoint of their society, though there are still questions about which groups of people should have the power to set answers [20].

Constructivism is particularly difficult to reconcile with the traditional view of scientific subjects. Constructivism assumes that knowledge is personal and subjective whereas, conventionally, science is predicated on the world being governed by reliable, discernible, and objective rules. This has consequences for gauging the effectiveness of constructivism as a paradigm since it is hard to perform meaningful evaluative studies [14].

Another difficulty associated with the constructivist paradigm is that the teacher occupies a supporting role and is therefore less able to direct proceedings. The focus of constructivism is on the student's experiential world and guiding the way in which they make sense of their own environment. The student must be in control of this process for it to be meaningful. As a result, a constructivist education is dependent on the student's passion and motivation. Constructivism asserts that learning is an active sense-making process on the part of the student, which requires concerted effort [14]. Constructivist learning tools do not support passive absorption of information, so if the student is not engaged then they will not learn.

Thus completes the analysis of two major educational philosophies. Until now, discussion has focused on the philosophical foundations of an educational system and the nature of the learning activities that are implied by that foundation, but this is not the only topic of interest. There is also a practical element to be considered – what do effective tools look like? What features should be included to encourage learning? These questions are universally relevant, regardless of the epistemological position of the teacher.

3.4 Practical Design

3.4.1 Universal Design for Learning

The universal design for learning guidelines (hereafter UDL) represent a collection of recommendations for producing educational material well-suited to teaching [21]. The guidelines are published by the organisation CAST, formally the Center for Applied Special Technology [22]. CAST have been working to improve the provision of education since their founding in 1984 and the guidelines are an extension of this effort. The guidelines concern every aspect of teaching process, such as instruction, practice, and assessment, and so context is important for determining which are relevant to a particular problem instance. The guidelines are separated into three distinct groups, each of which is concerned with a different aspect of the learning process. This section will outline the three categories and discuss the ability of educational technology to meet each recommendation.

Engagement

"The Why of Learning" – instilling interest in the subject, thereby motivating the learner to study.

Engagement refers to the process of motivating a student's learning, from inspiring the initial interest in the topic through to developing strategies for self-regulation. It is necessary to design material with engagement as a consideration because "information that is not attended to, that does not engage learners' cognition, is in fact inaccessible." [21]. By cultivating student enthusiasm, an educational system can cause learners to invest more time and energy in studying, thereby improving their outcomes. The universal design for learning guidelines give multiple recommendations for improving engagement through design decisions.

A key method is to give students freedom to determine the methods by which they are taught. While it does not make sense to allow students to choose the overall learning objective itself, students can be engaged through teaching methods that are most able to capture their interest. By allowing students "discretion and autonomy" to control factors such as "the level of perceived challenge" and "the type of rewards or recognition available", Cast contends that "pride in accomplishment" can be instilled in a student, incentivizing them to continue their academic journey [21].

UDL encourages designing materials to be relevant to the student's life to maximize their engagement. Individuals are more motivated when they perceive the learning material as being directly relevant to their interests, so it is important to integrate social and cultural context into teaching activity. Furthermore, it is beneficial to impart the function of the concepts that are being studied so that the student appreciates its value. Creating material that engages the student is an important aspect of the design process, but it is equally important to minimize factors that threaten engagement.

UDL guidelines recognize the importance of eliminating distractions and perceived threats from a student's environment. When students are struggling with factors either external or internal to the learning environment, they are unable to concentrate on their work. This effect can be minimized by "creating an accepting and supportive environment" [21]. In addition, the threats that a student might perceive are varied and personal. Some students can be distracted by learning materials that are excessively stimulating, while others may struggle with anxiety relating to public evaluation. Consequently, removing these threats involves a degree of individualisation. In practice, varying the types of activities with respect to distracting attributes, such as the levels of background noise, the number of items presented at a given time, and the duration of sessions helps to ensure that every student has some period of concentrated work.

Educational technology has several inherent advantages for maximizing engagement over other forms of educational material. The use of technology permits student interactivity to a degree that is impractical to expect of a teacher alone. The learner can enter answers into the system and receive immediate feedback, or interface with the computer in creative ways such as dragging entities around the screen or manipulating a computer model. Furthermore, computers allow different students to receive the same material through different combinations of visual, aural, and kinaesthetic teaching. These advantages fit better into a constructivist paradigm, where the teacher is viewed as less integral to the process.

Representation

"The What of Learning" - refers to how course material can be presented in a variety of ways to facilitate deep understanding.

A key feature of good representation is control of the student's perception. Information should be presented in such a way as to allow the student to derive the greatest degree of meaning from it. The forms of information communication that are most effective varies from student to student, so material should be provided in multiple forms to be accessible to everyone. UDL recommends "providing the same information through different modalities" [21] and allowing for the user to adjust how they receive this information, through design considerations such as offering customization options for the information display and presenting information using a combination of auditory and visual techniques.

It is also important to ensure effective use of language and symbols. Ultimately, information is transferred through language, so student sense-making is highly dependent on the clarity of the resource text. UDL guidelines stress clarifying relevant vocabulary and symbols, especially for mathematics, and to provide support for multiple languages where possible. In this way, information can be transmitted to the student efficiently, but this is only the first step, it is also necessary to ensure that the student is able to understand and process the information that they are receiving.

The final section of the UDL guidelines for representation is comprehension. Comprehension is concerned with helping the student to put the learned material into a wider context, linking it to previous lessons and ideas, and being able to generalize their knowledge to new situations, not directly covered by the teacher. Comprehension is vital for deep, long-term understanding of the subject matter.

Action and Expression

"The How of Learning" – Provide freedom for the student in how they express what they have learned.

The final section of the UDL guidelines concerns action and expression. It is important to provide choice in how a student "can navigate a learning environment and express what they know" because "there is not one means of action that will be optimal for all learners" [21]. Guideline four, physical action, focuses on controlling how the user can interact with learning resources. The design principles for achieving this are to provide variety in how students can navigate the material and to provide access to assistive technologies in contexts where the student has some impairment to their ability to interact. The benefits of adequate provision of assistive technology are well documented. For example, a study examining how speech recognition technology for essay writing affects the scores received by students with learning disabilities found a statistically significant correlation with improved results; a phenomenon attributed to students feeling encouraged to use longer words [23].

The next guidelines involve expression and communication. Materials should be designed to use multiple modes of communication and provide a variety of tools for "construction and composition" [21]. The student should be permitted to find tools that are a good match for their personal style of work and the task to be completed. The student should also be given access to a range of tools that help them organize their understanding and demonstrate their knowledge of the relationships between the topics that they have studied.

Thus ends the discussion concerning educational theory. The next task will be to examine empirical modelling theory and practice to determine its suitability for building educational tools on a theoretical level. The concepts discussed in this section will be vital for evaluating the potential of Empirical Modelling for use in an educational context.

3.5 Empirical Modelling

3.5.1 Introduction

Empirical modelling is a modelling paradigm that focuses on the human understanding of a topic area. Its goal is to facilitate the construction of "interactive artefacts that serve a role in sense-making and learning", called construals [24, p. 2]. In effect, allowing the modeller to use a computer as a medium for thought. In this way, Empirical Modelling differs from more conventional modelling philosophies by allowing for informal, incomplete modelling of concepts rather than the formal, rigorous approach that is generally demanded.

Empirical Modelling has developed over twenty years of active research and there is continued interest in further refining its methods, philosophy, and practice. This section will introduce the philosophy, concepts, and terminology that constitute Empirical Modelling as a theoretical subject, as well as explore the tools and notations that are used for Empirical Modelling in practice. The information that follows about the history of Empirical Modelling was acquired during a conversation with Meurig Beynon in May 2021. Meurig Beynon has been a key participant in the field of Empirical Modelling since the outset and is highly informed about its history and principles.

The history of Empirical Modelling began in 1982, when Nader Farahnak, a third-year project student, created a notation called "Aid for the Realisation of Combinatorial Artefacts", or ARCA. ARCA raised some interesting questions with respect to the role of computing, in particular the difficulty of producing computational models to test some mathematical conjecture which can be updated conveniently as understanding of the problem area developed. ARCA's design was built on modelling states from the perspective of an agent and building connections through the modeller's experience, which gave it potential for building models that were more interactive and manipulatable than the functional programming approaches that were prevalent at the time. ARCA was the first of the 'Definitive

Notations' that support Empirical Modelling.

In 1986, a new notation called LSD was developed for modelling concurrent systems in telecommunications research. LSD defined some of the key features of Empirical Modelling that caused it to develop into a distinctive modelling philosophy. LSD modelled a system state using concepts such as oracles and derivatives, which describe features of the system state that can be affected by an agent and features that have a value dependent on an oracle, respectively. The essence of oracles and derivatives remain in the concepts of observables and dependency that are in use in Empirical Modelling today. An LSD model was effective at capturing the relationships between features of models, representing the prescribed ways in which the system could be interacted with, and demonstrating how those prescribed changes would affect other features of the model.

More recently, tools such as EDEN (Evaluator for Definitive Notations) have been developed to support Empirical Modelling activities by showing how definitive notations can be applied to programming more generally. A JavaScript version of EDEN called JSEden also exists, alongside a more recent project called Construit! which serves as a development environment for JSEden models. Construit! is a practical, modern tool for creating models in the Empirical Modelling style, called construals, and serves as the main method of doing so in this report.

It is impossible to fully appreciate Empirical Modelling without discussing Radical Empiricism. Radical Empiricism serves as the philosophical basis for the Empirical Modelling approach, providing the foundations of the experience-focused and observation-based methodology that lie at the heart of Empirical Modelling as it is practiced today. An outline of the beliefs and theory that constitute Radical Empiricism will inform analysis of Empirical Modelling by providing insight into the nature of the models that are produced.

Radical empiricism is a system of epistemology championed by William James, who published a series of essays detailing his philosophy [25]. It is most distinguished by the role it affords experience as the centre of knowledge. Like other philosophies in the empiricist tradition, radical empiricism views experience as whole in the sense that any act of knowing derives from experience such that there is no need to refer to entities and concepts that cannot be perceived empirically. Further, radical empiricism suggests that experience is rich with a wide range of meaning, values and connections that must be considered in addition to its base, physical characteristics. Knowledge in radical empiricism therefore consists both of direct observations, and meaningful connections between them.

This view of experience leads to the conclusion that knowledge is not fixed because it derives from trying to makes sense of a body of experience that is far richer in detail than it could ever hope to contain. There is no guarantee that the concepts and relationships that a person uses will always be appropriate since human experience shifts and grows, rendering outdated the previous models of thought that were used to explain it. As a result, knowledge in radical empiricism must constantly be adapted and reorganized to better fit experience. [26]

Empirical Modelling has close conceptual links to radical empiricism and is aimed at modelling the ”state-as-experienced” [27]. It is inspired by radical empiricism in the sense that modelling in a practical sense is built on defining features of experience and the relationships between them. This leads to a very personal modelling paradigm, in which the meaning of a model is derived from its relationship to the modeller's experience. The features and relationships that they define allow the model to display how changes in base state are expected to propagate in the developer's experiential world from which the model is defined. Interestingly, this allows the modeller to represent their knowledge of a subject externally on a computer screen, such that they can critically evaluate the model from an outside perspective.

This foundation serves to differentiate Empirical Modelling from other modelling paradigms. Empirical models reflect current understanding of a subject based on the modeller's experience, but future experience may change this understanding. Thus, it is unknown exactly how a construal will appear and function as its development proceeds - it effectively has no preconceived behaviour [27]. This differs greatly from conventional computer science where models are typically assumed to be fully understood before work on their implementation even begins and correspond to a well-defined concept with an unchanging specification. As a result, in keeping with radical empiricism, a construal is never truly complete - it only models the conceptual framework of the modeller within their experience at a given time.

3.5.2 Modelling Features

In an attempt to model relationships between experience, models based on Empirical Modelling consist of three main features: observables, dependencies, and agency.

Observables are the primitive elements of a construal, they describe a feature of the user's experience that can be perceived and associated with a value. They are not limited to physical constructs, but can also refer to mental structures that the modeller projects onto their experiential world. Dependencies refer to assumed relationships between observables, corresponding to an expectation of how changing the value of one feature can affect other features. Agency refers to entities in the model that are believed to have the ability to affect a change of state. The most obvious agent is the modeller who can manually change observables.

A statement in Empirical Modelling is called a definition. Systems for expressing these definitions in a meaningful way are known as definitive notations.

3.5.3 Analysis

An aspect of Empirical Modelling that is important in the context of educational paradigms is that it results in external artifacts. While a feature of general modelling, and not limited to Empirical Modelling in particular, it is important to note the significance of the models that are produced. Both instructionism and constructivism have been criticised for their assessment methodologies. In instructionism, students are tested on their ability to answer familiar questions, which does not guarantee true understanding of the subject matter, whereas in constructivism it can be difficult to choose meaningful assessment methods due to the focus on the personal nature of knowledge. Model building could offer a potential solution since the models that result provide insight into the student's understanding. It is possible that a form of assessment could be derived that makes use of these models, such as asking the student to build, repair, or complete a model for a topic in the exam. Assessment is not the only advantage of physical artifacts.

Outside of assessment, by producing models, students are able to examine their understanding from an outside perspective. By creating a model and manipulating it, students may be able to identify weaknesses in it, and since in Empirical Modelling, student knowledge is directly represented by the construction of a construal, weaknesses in the construal imply that there is potential to refine the student's understanding. This implies an important paradigmatic distinction between modelling and other forms of educational technology - models are not only a computerised form of traditional educational practice, but an integral part of the process. It signals a new paradigm for educational technology in which a student does not merely use a computer, but 'thinks' with one. This could represent the educational paradigm built for technology for which Albirini is searching [16]. The benefits of models are not limited to the students.

Teachers also benefit from being able to use the models made by their students to inform their teaching activities. A teacher can see not just the answers a student gives to a set of questions but gain insight into their entire understanding of the topic that is being taught. In this way, a teacher can observe features of their students models that are inaccurate within their own experience, and guide the student to understanding that may allow them to improve their model. Additionally, they can use the models to determine the understanding of a topic area that their teaching has instilled in a student and perhaps update their methods to avoid any misunderstandings that resulted. These advantages are, at least in theory, applicable to all modelling paradigms, but Empirical Modelling has some features that could encourage its use over its rivals.

A key feature of Empirical Modelling is that the models it produces are personal to the modeller and rooted in experience, which links to a constructivist educational philosophy. In constructivism, learning is guided by the student with emphasis on their modes of thinking and conceptual framework. If educational technology is to support this form of education, it must have the flexibility to adapt to the student's understanding and knowledge. In this sense, Empirical Modelling could be viewed as a more appropriate modelling paradigm for education than procedural and object-oriented alternatives, since personal sense-making is an inherent part of its design whereas those other approaches typically depend on having a strong understanding of the model before it is built. This is not the only striking link between Empirical Modelling and constructivist practice. The sense-making property of Empirical Modelling is supported in several ways.

First, dependency is a powerful concept for rapid refinement of a model. To express the Empirical Modelling concept of dependency using a procedural language requires significant effort to implement because the modeller must detect when the base observable changes and update derivative observables accordingly. If the modeller subsequently decides that a different set of dependencies would be more accurate, it would require rewriting multiple lines of code and potentially a change to the overall structure of the program. In the Empirical Modelling paradigm, however, dependencies can expressed as a single definition and therefore are easily adapted if the modeller's understanding of the model changes. This demonstrates a useful characteristic of Empirical Modelling as a paradigm, especially where models are not rigorously structured beforehand and so more susceptible to change.

Another way in which Empirical Modelling supports student sense-making is the nature of observables as being founded in experience. The nature of an observable is that it monitors the value of something that the user actively perceives, thus it refers to something with an intuitive meaning in the mind of the modeller. Since observables correspond to an observation in experience, and dependency is a perceived relationship between observables, each aspect of the model is directly related to the modeller's experience and not obfuscated by abstract concepts. This strong connection to experience is valuable in an educational context because it causes models to be oriented towards human thought processes and thinking rather than formalism.

The artifacts that Empirical Modelling produce are open and adaptable because the modeller is free to change and expand their models as their understanding of the topic is refined, which has parallels with the constructivist view of knowledge development. A key tenet of constructivism is that knowledge is never beyond doubt, it changes as a person's experiential world expands. Consequently, any modelling paradigm that supports constructivist teaching must produce malleable artifacts that provide the student with the opportunity to develop their understanding over time. By this criteria, Empirical Modelling is a good paradigm for education because the freedom it provides in redefining previous dependencies makes it extremely adaptable, and the powerful programming tools it provides give the user the ability to build the construal in any way they can imagine because they are not limited by the scope of a custom modelling environment. These features also connect to UDL guidelines 7.1 and 7.2, which encourage providing the student with autonomy and maximizing cultural relevance, because the modeller has complete freedom to express their knowledge in a powerful, but accessible, way.

Empirical modelling is also a strong candidate for fulfilment of UDL guideline 5.2, which recommends providing tools to aid in the construction of knowledge, such as concept mapping tools. The nature of empirical modelling makes it inherently well suited for this task, as it is designed to produce models that represent student knowledge understanding in a direct sense.

Overall, Empirical Modelling seems a strong candidate as a basis for educational technology. It combines many of the strengths of modelling paradigms with unique benefits that derive from the personal, experiential approach that Empirical Modelling espouses. At this stage, this analysis is only supported by a comparison of the profile of the Empirical Modelling paradigm with the requirements of education that were outlined in the previous section. This is not sufficient evidence since these theoretical benefits may fail to materialise in practice. To gain more insight into what Empirical Modelling tools might provide, it is important to develop resources to exploit some of the advantages that have been mentioned above.

Chapter 4

Practice

4.1 The Construit! Environment

4.1.1 Introducing Construit!

Construit! is an environment for Empirical Modelling that was developed in 2014 with funding from the ERASMUS+ Programme. Its stated aims are to ”introducing new principles and tools for a computing practice that enables educators and learners to collaborate in creating live interactive resources” [28]. It differentiates itself from other approaches to educational technology by the personal nature of the models that result, such that they constitute ”shareable ‘working models’ or understandings” [28] This section will explore the structure of the Construit! environment in a top-down fashion, beginning with the pages that compose the environment before moving onto the features and semantics of the language that it supports.

Construit! is a development environment for the JSEden language, which is based on the Empirical Modelling philosophy. It is currently accessible online at https://jseden.dcs.warwick.ac.uk/construit/ and consists of several organisational pages and a web-hosted interpreter.

As with all models, the best way to understand the construals shown below is to experiment with them. The reader is therefore encouraged to load each construal in turn using the links provided. Nonetheless, the explanations provided aim to give a good account of the key concepts that are being discussed such that personal interaction with the construals is not necessary.

4.1.2 Construit! Organisation

Homepage

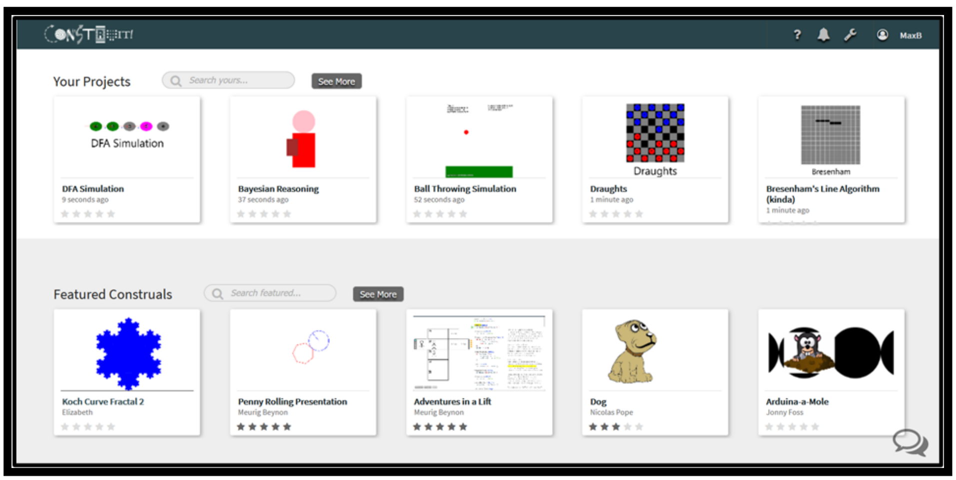

Figure 4.1.1: The Construit! Homepage

Figure 4.1.1 shows the first page the user sees upon logging into the Construit! site, hereafter referred to as the home page. The home page is a staging point for the user to organize their construals and browse those of other contributors. Each rectangle represents a construal, which is saved with an image and a title to allow for searching and easy identification of a construal's topic. Additionally, Construit! allows for rating construals and leaving comments, thereby allowing a degree of feedback and collaboration.

A component of constructivist philosophy is that advanced knowledge is built on fundamental knowledge. This is supported in Construit! by the ability to build construals on top of other construals. In a similar fashion to how packages might be imported in standard programming languages, the user can import a construal to use the observables and dependencies that are defined within it. In this way, the student can link their previous construals to the newer material that they are taught and thereby form links throughout the subject.

Construal Popup

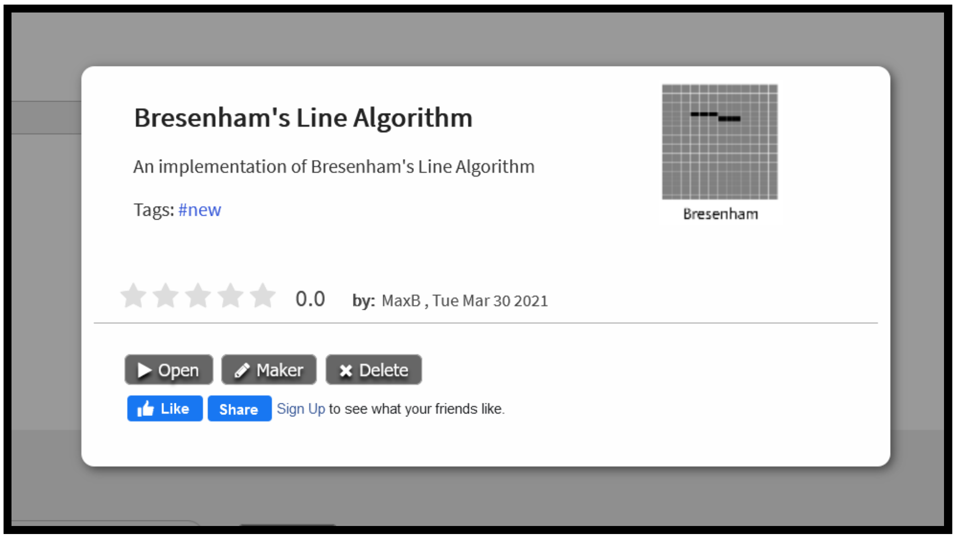

Figure 4.1.2: Construal Popup

Figure 4.1.3 appears when the user double clicks on a construal. It shows the title, rating, comments, and description of the construal that has been selected. It also displays the date on which the construal was last updated and the tags that are associated with it for searching.

A Construal

Construit! offers significant freedom with customizing the appearance of a construal, but figure 4.1.3 is a typical example. A construal takes the form of a booklet with pages that the user can turn. The text is a mixture of code and comments, with the picture being described by statements within the program itself.

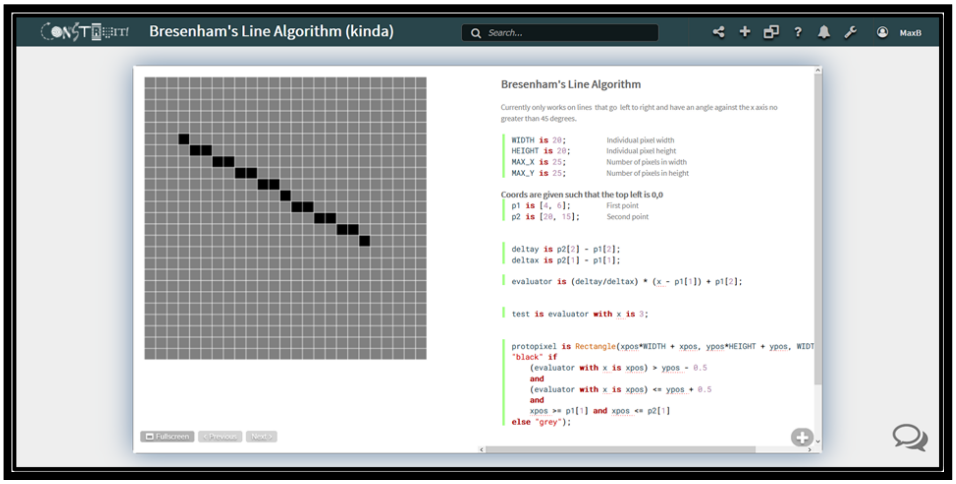

Figure 4.1.3: Example of a Construal

4.1.3 JSEden Language

JSEden is the programming language that is supported by Construit! It is based on a definitive notation called Eden. JSEden is aimed at supporting Empirical Modelling by allowing construals to be represented on a computer. Since JSEden is a tool for developing models based on the Empirical Modelling paradigm, it must provide methods for representing the principal components of a construal: observables and dependencies.

JSEden implements the concept of observables in Empirical Modelling, using a construct also called an observable. One of the roles of an observable in JSEden is to model a feature of the creator's direct experience, such as the height of a table or the time since waking up. In this role, observables are comparable to variables. Construit! supports a range of standard data types, including strings, integers, floats, booleans, and python-style lists. The user can declare an observable and assign it a static value using the following code:

```
observable = 1;
observable2 = "chair";
```

```
observable3 = true;
observable4 = [5, 6.4, "hello world"];
```

Instantiated observables can be examined at any time through the use of an observable list, shown in figure 4.1.4.

Figure 4.1.4: An observable list

Observables are not limited to this functionality, they can also be assigned a dependency.

Dependency is modelled using the keyword "is", which links the value of an observable to an expression. When the value of the expression changes, the observable updates in a manner reminiscent of a spreadsheet formula. Dependency is a powerful tool for modelling relationships between concepts, which is an important aspect of both Empirical Modelling and Radical Empiricism. A dependency can be defined using code such as:

```
x = 4;
y is x * 3;
```

In this example, if the value of x changes to 7, then y will automatically update to 21. This can cause cascading updates if there a sequence of observables where each is dependent on the previous. As a result, dependency in JSEden is extremely powerful because complex observables can be built up by stacking dependencies that update automatically when the base state of the model changes. For example, consider a model of the solar system. The position of the moon is dependent on the position of the Earth, which is dependent on the current stage of its orbit. If the Earth continues its orbit, that change will propagate upwards through the position of the Earth and into the position of the moon.

In addition to expressing an observable as being dependent on a mathematical expression, there is the option of using a conditional statement to change the value of observable according to a given condition.

```
x is 4 if y < 3 else 10;
```

In this case, observable x takes the value 4 whenever y is less than three, but changes to 10 otherwise.

To create an observable, the user clicks the green "play button" next to the relevant line.

Dependencies update automatically when a line of code that updates the value or dependency of an observable is run, but it is also possible to trigger updates dynamically with continuous observable values. The user clicks and holds the play button next to a line of code that describes an observable's dependency until a lightning bolt appears. Then, any integers in the dependency description can be dragged left to decrease the value, or right to increase it. Any dependencies that contain that observable will be updated in real time as the value changes.

This feature allows for interesting interactive behaviour to be built into models. For instance, in a construal that models the trajectory of a ball, where the ball's position can be controlled continuously from launch to landing by dynamically updating the model time.

Dependencies can be layered to form increasingly sophisticated observations about the model state. For instance, an observable to determine whether a player has been checkmated in the game of chess could use a dependency involving the positions of the pieces, their different movement capabilities, and their colours. The positions involving equally complicated dependencies concerning player agency and previous board states.

Beyond observables and dependencies, Construit! offers two other main keywords: when and with.

A when statement consists of the keyword and a condition, followed by a code block:

```
when (condition) {
    Execute this code
}
```

The when statement will trigger whenever the condition is met, then execute the code in the block. To continue the chess example, a when statement could be used to detect when a pawn has reached the end of the board and should be promoted.

The with keyword is more complicated. The user can define a kind of 'prototype' observable that is dependent on non-instantiated observables. Then, a second observable can be created that is based on the prototype, using the with statement to instantiate the dependency.

```
prototype is x * 3;
actual is prototype with x is 5;
```

Here, the value of 'actual' will be 15. If the definition of 'prototype' changes, it will propagate and the value of 'actual' will update.

In addition to the features related to Empirical Modelling, Construit! also provides access to a number of standard procedural programming constructs. The creator can use for loops, while loops, and if-else statements with c-style syntax. Some relationships are best expressed procedurally, it is left to the modeller's judgement to use the tools that are most appropriate for a particular problem.

4.1.4 Graphics

A major element of Construit! is the ability to draw and manipulate simple graphics programmatically through observables. The code for using graphics is simple and flexible, with the ability to produce complex behaviour through the layering of dependencies. Graphics can be drawn to the screen by passing them to the special observable 'picture'. One of the most basic graphical operations provided by Construit! is to draw simple geometric shapes.

Construit! allows the creator to define and display a shape with only two lines of code. First, define an observable which depends on a shape function, then pass it as a dependency to the 'picture' observable. For example, the code to draw a square would be:

```
shape is Rectangle(20, 20, 50, 50, "blue");
picture is shape;
```

There are six shapes that can be drawn in this way, as demonstrated in figure 4.1.5.

In addition to basic shapes, methods to interact with the construal, such as buttons and sliders, are also supported. They can be created in the same way as shapes. Creating an input element automatically defines observables corresponding to its state, as shown in figure 4.1.6.

4.1.5 Formatting Tools

In addition to the functional and graphical elements that Construit! provides, there are also formatting tools for presenting and organising code in a clear, comprehensible way.

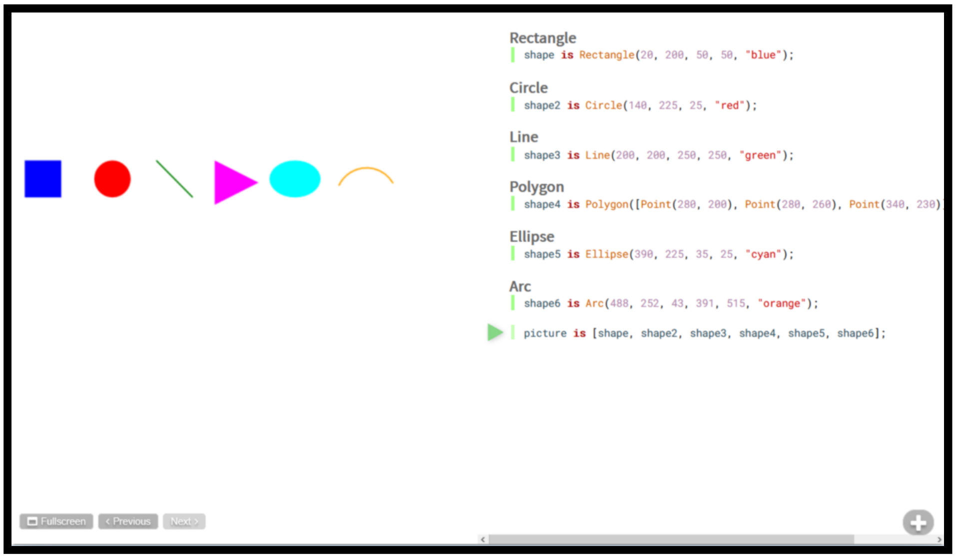

Figure 4.1.5: A demonstration of shapes in Construit!

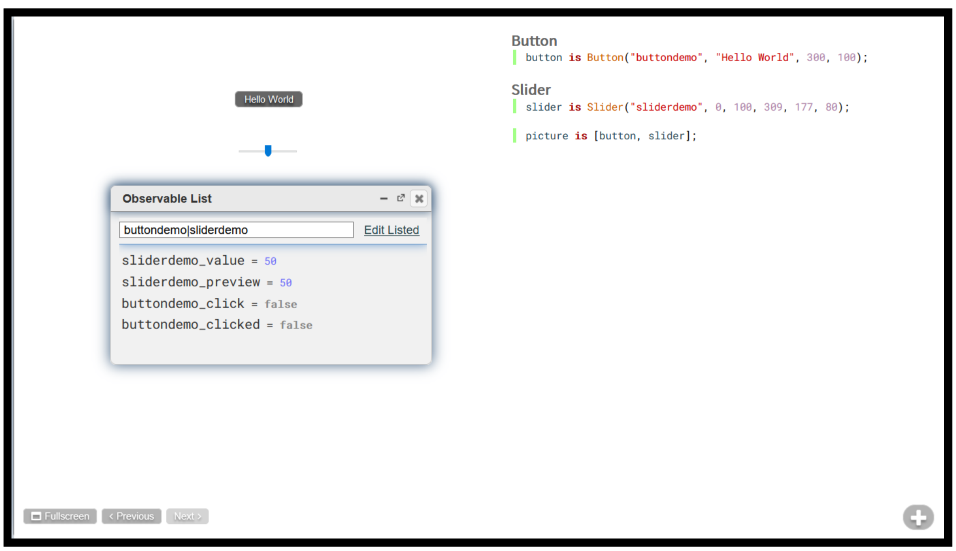

Figure 4.1.6: A demonstration of input elements, including observables

Construit! includes a set of observables with special significance, which allow the user to influence the appearance of a construal. Some of the characteristics that can be controlled in this way are the screen width, book ratio, and x. Since these traits are treated as observables, they can be changed arbitrarily at any time and even assigned a dependency.

Construit! includes the ability to use regular expressions to search through instantiated observables. The creator can use these to show and hide sets of observables depending on which they think is most valuable for the user to see. The active regular expression can be changed at any time, either manually or with a function call (showObservables()).

Markup

Within the construal booklet itself, the environment provides markup tools for customizing the appearance of text, as described below:

Markup	Effect
#Text	Comment
##Text	Big Header
###Text	Small Header
Text*	Italicize Text
*Text**	Bold Text
#[text](address)	Create a link to the address with the text
#(ACTIVE>observable)	Embed observable into the text
#* Text	Create a bulletpoint item
#> Block Quote	Create a block quote
#[text]{colour}	Colour text
#—	Create horizontal line

The existence of these markup tools has interesting implications for Construit's use for building educational resources. The most direct observation is that they relate closely to the universal design for learning guidelines which encourage providing options to change text formatting and presentation.

Furthermore, they provide a resource creator with options for customising their material in a way that harmonises with their vision for the project. A teacher can

Figure 4.1.7: A demonstration of the formatting features

emphasise important facts, procedures, and ideas to assist the learning process for their students. Additionally, learners can format the resources in a way that appeals to their studying style – assisting in the sense-making process. In this way, Construit!'s markup capability is a valuable tool to be built into the environment.

While these formatting tools are important and useful in an educational context, they are not what make Construit! especially well suited to the task. The ability to customize a resource is a natural application of technology to the domain of learning and is therefore already well explored. Common learning tools, including presentation software such as Microsoft Powerpoint, generally contain sophisticated formatting capabilities as an industry standard. Therefore, Construit! formatting options are a beneficial inclusion, but Construit! is truly separated from its rivals by deeper, conceptual differences.

4.2 Construals

4.2.1 Bresenham's Line Algorithm

Introduction

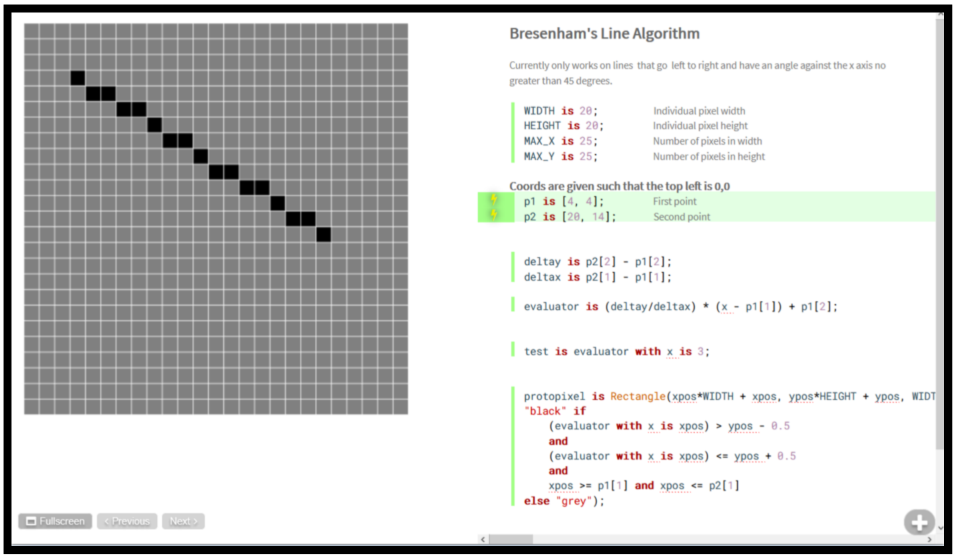

Figure 4.2.1: The Bresenham's Line Algorithm Construal

Link: `https://jseden.dcs.warwick.ac.uk/construit/?q=:me&load=517&vid=14490&r=`

Bresenham's line algorithm was the first construal created as part of this project. The main purpose was to build familiarity with the language as the problem is simple, but the construal does have educational value as Bresenham's line algorithm is a standard algorithm used in computer graphics. The code is short, consisting of only a page, and is a good introduction to practical usage of Construit!.

Bresenham's line algorithm is an efficient method for 'rasterizing' lines – converting infinitely thin mathematical lines into a set of square pixels on a screen. The algorithm works by using an equation to calculate the next pixel to draw, then continuing until the end of the line is reached. The main benefit of Bresenham's line algorithm is that it does not use multiplication or rounding operations, and so can be calculated quickly.

At the time of the construal being created, the algorithm was new to the author. This is reflected in the construal not being faithful to the algorithm since it does use multiplication and division operations. The construal creates dependencies for a square of 'pixels' that are passed to the "picture" observable. There is also an 'evaluator' observable that represents the y value of the line at a given point x. A given pixel should be chosen if its y value is the closest to the evaluator value at its x position. The colour of these pixels is dependent on whether Bresenham's line algorithm 'chooses' them when the line is drawn. They are defined as follows:

```
protopixel is Rectangle(xpos*WIDTH + xpos, ypos*HEIGHT + ypos, WIDTH, HEIGHT,
"black" if
(evaluator with x is xpos) > ypos - 0.5
and
(evaluator with x is xpos) <= ypos + 0.5
and
xpos >= p1[1] and xpos <= p2[1]
else "grey");
```

With WIDTH and HEIGHT representing the width and height of the pixels. This 'prototype' pixel is then instantiated using:

```
pixels is protopixel with xpos is 1..MAX_X, ypos is 1..MAX_Y;
```

Which creates a two dimensional array of pixels.

4.2.2 Deterministic Finite Automaton

Introduction

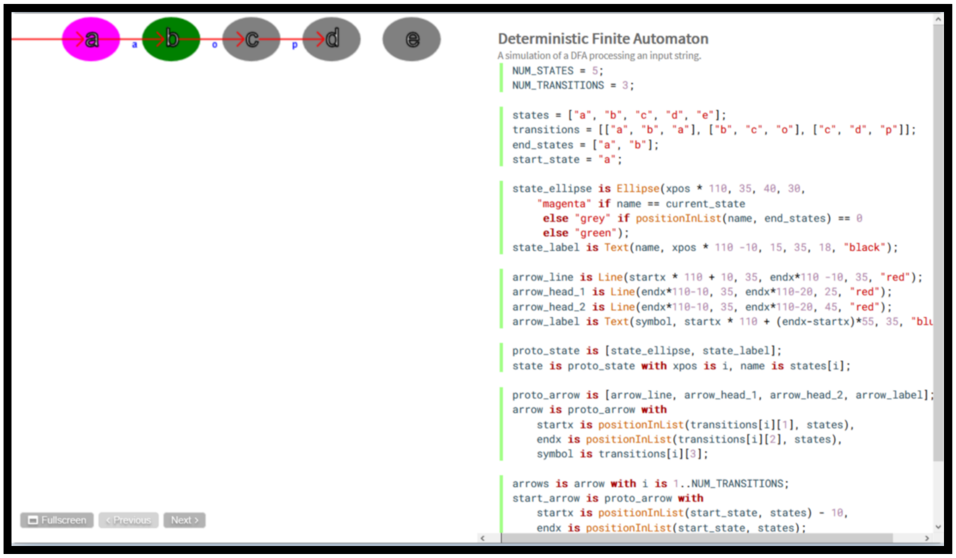

Figure 4.2.2: The Deterministic Finite Automaton Construal

Link: `https://jseden.dcs.warwick.ac.uk/construit/?load=518&vid=14494&r=`

This construal simulates a deterministic finite automaton (DFA), which is a commonly used construct in Computer Science for modelling state transitions. A deterministic finite automaton consists of a set of states; a set of transitions mapping one state to another; a set of accepting states; an alphabet, denoted by a sigma; and a single starting state. A DFA can be given a string to classify. Beginning at the starting state, the characters of the input string are consumed sequentially. With each character, the DFA state changes according to the defined transitions. When the string has been fully processed, if the final state is an accepting state, then the string is accepted, otherwise it is rejected. The set of strings accepted by a DFA is called its language.

The user inputs the states, transitions, end states, and start state, which are used by the construal to create an image of the DFA using primitive shapes (Figure 4.2.3). The user can define an input string and run a block of code that will consume the next character in the string and update the current state of the DFA accordingly (Figure 4.2.4).

The most interesting aspect of this construal is the use of dependencies in its graphics. The colour of a state is dependent on its status: magenta if it is the current state; green if it is an accepting state; otherwise grey. These dependencies are built on the observables that monitor the current state of the automaton, such as the starting states that the user declares explicitly, using a dynamic if-else statement.

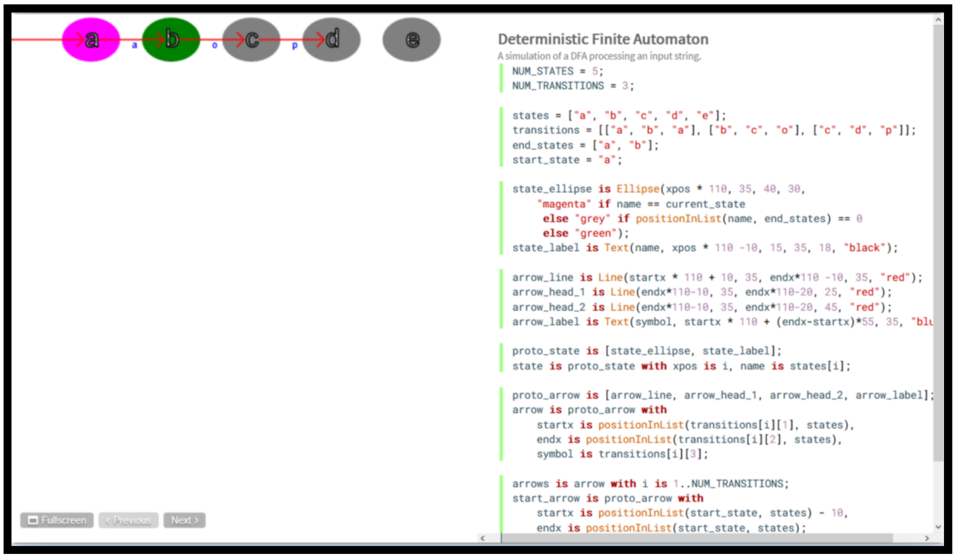

Figure 4.2.3: DFA after initialisation

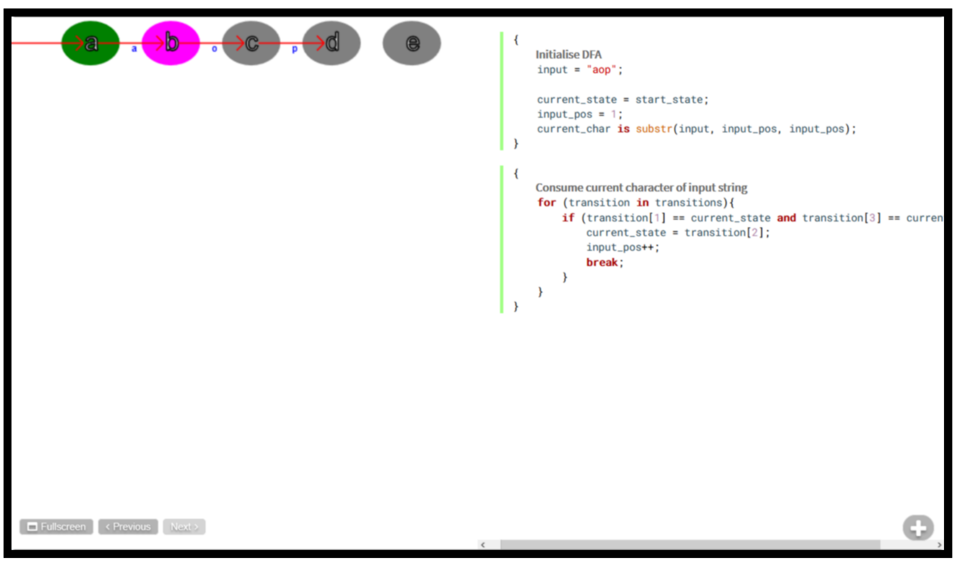

Figure 4.2.4: DFA after consuming an ”a” from the input string

4.2.3 Draughts

Introduction

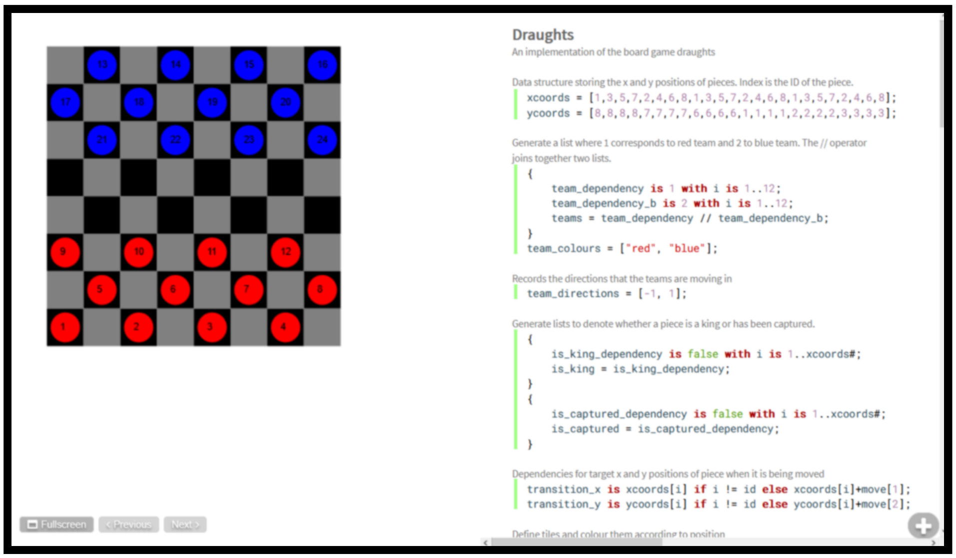

Figure 4.2.5: The Draughts Construal

Link: `https://jseden.dcs.warwick.ac.uk/construit/?q=:me&load=520&vid=14491&r=`

Draughts is a more complicated construal that demonstrates some of the other features of Construit! It was created after Bresenham's Line Algorithm to develop further familiarity with Construit! by completing a more difficult project. The aim of the construal is to implement all the functionality of the board game draughts using JSEden. The main purpose of this construal is to practice using the language for more sophisticated projects.

The game of draughts begins with a board with pieces on it and two players. The players take turns moving a piece to somewhere else on the board, following the rules for legal piece movement. Pieces move diagonally and can take an opposing piece if it is adjacent. Pieces can only move forward until they reach the end of the board, then they become a 'king' and can move forward or backward. A player wins when their opponent has no pieces remaining.

The construal begins by defining a set of observables that represent the tiles on the board, these observables are passed to the “picture” observable. Then the construal creates lists to hold some properties of the pieces: their x and y coordinates, their colours, whether they have been captured, and whether they are a king. These are the observable features of the game board that will be used by dependencies to discern more abstract, game-relevant concepts.

The user can move a piece by inputting its number and the move they wish to make into observables, then running the code block that will perform checks and move the piece. The checks are performed procedurally, using procedural if statements such as:

```
if (target_x <= 0 or target_y <= 0 or target_y > 8 or target_x > 8) {
    current_msg = "Invalid Move: Square does not exist";
    valid = false;
}
```

A when statement detects when a piece should become a king, by triggering whenever a piece reaches the end of the board, then scanning the piece positions and ‘promoting’ any piece that qualifies.

It was created towards the start of the project and therefore also provides an example of poor design that are instructive to discuss. The validation checks performed on a move before it is executed are implemented procedurally. In retrospect, this is not sensible since the various conditions that must be met for a move to be legal are all independent features of the model and are therefore better represented by observables and dependency.

4.2.4 Ball Throwing Simulation

Introduction

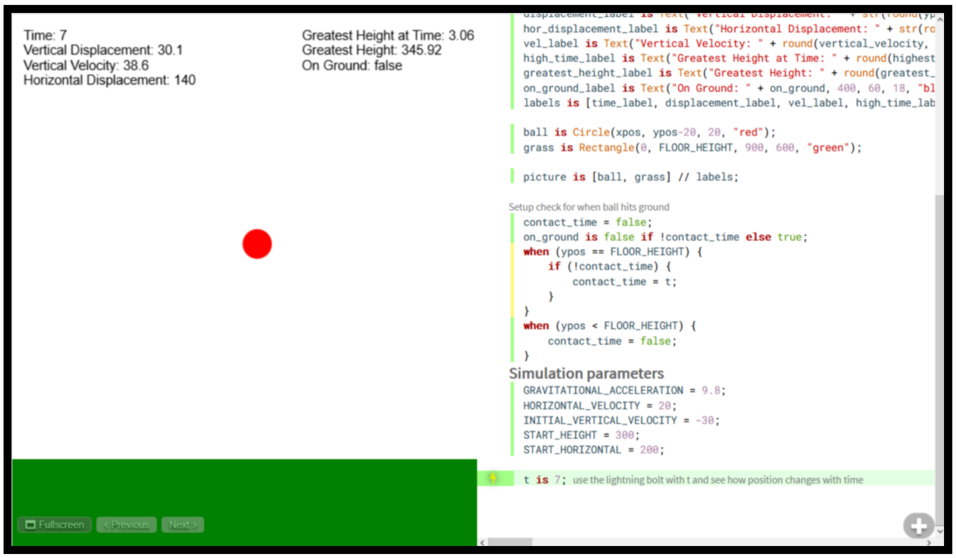

Figure 4.2.6: The Ball Throwing Simulation Construal

Link: `https://jseden.dcs.warwick.ac.uk/construit/?q=:me&load=523&vid=14492&r=`

The ball throwing simulation construal demonstrates usage of the SUVAT equations. The SUVAT equations link five properties of an object in motion: displacement, initial velocity, final velocity, acceleration, and time. They come from the fields of physics and mechanics. The construal uses these equations to model the motion of a thrown ball.

This construal is the first example given that is deliberately directed towards a formal, academic subject. It marks the transition from projects aimed at building familiarity with Construit! to using the knowledge gained to build educational construals that can be evaluated. The experience of building this model, and the others to follow, provides insight into any potential value Empirical Modelling might have for the modeller. Additionally, the finished model can be related to the ideas and criteria outlined in the educational theory section to find evidence of harmony with prevailing ideas on effective education.

The construal is simple as it does not use more than two stacked dependencies. The user can control the parameters that describe the initial state of the ball, then simulate how the ball moves in both the horizontal and vertical directions as time progresses. The ball's displacement and velocity are modelled using dependencies based on the SUVAT equations, and other characteristics of the ball's trajectory such as its greatest height and the time that height was reached are calculated in a similar fashion. For example, the current height of the ball is expressed using a dependency based on the equation $s = ut + \frac{1}{2}at^2$:

```
calculated_y_pos is START_HEIGHT + (INITIAL_VERTICAL_VELOCITY * t +
                             0.5*GRAVITATIONAL_ACCELERATION*t*t);
```

The position of the ball is a dependency on 'calculated_y_pos, so as the user redefines the time observable 't', the ball moves on the screen automatically.

4.2.5 Beachside Commerce

Overview

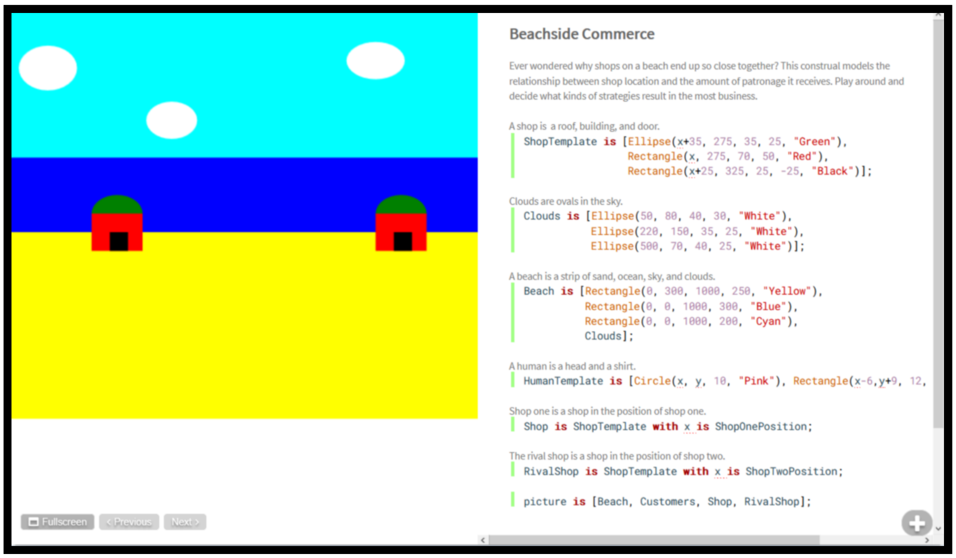

Figure 4.2.7: The Beachside Commerce Construal

Link: `https://jseden.dcs.warwick.ac.uk/construit/?q=:me&load=552&vid=14323&r=`

The Beachside Commerce construal is based on a concept known as “Hotelling’s Law” [29], which it aims to to teach the user about using an interactive, constructivist-style teaching methodology. It achieves this by building a simple model that the learner can interact with, explore how positioning a shop affects the business it receives, and form conclusions – gaining a deep understanding in the process.

To understand the idea, imagine a beach that has two shopkeepers who want to open their business somewhere along it. If there is no discernible difference between the two stores, then customers will tend to visit whichever is closer. Both shopkeepers therefore aim to place their store such that most customers are closer to it than to its rival. As a result, the two businesses will tend to be positioned directly next to each other, in the centre of the beach.

When the two shops are positioned equally far from the centre of the beach, the patronage received by each is approximately the same. This situation is not stable since either shop would benefit from moving towards the centre and taking a larger share of the customer base. The user can model this by moving the shops around the beach and observing how the number of customers received changes.

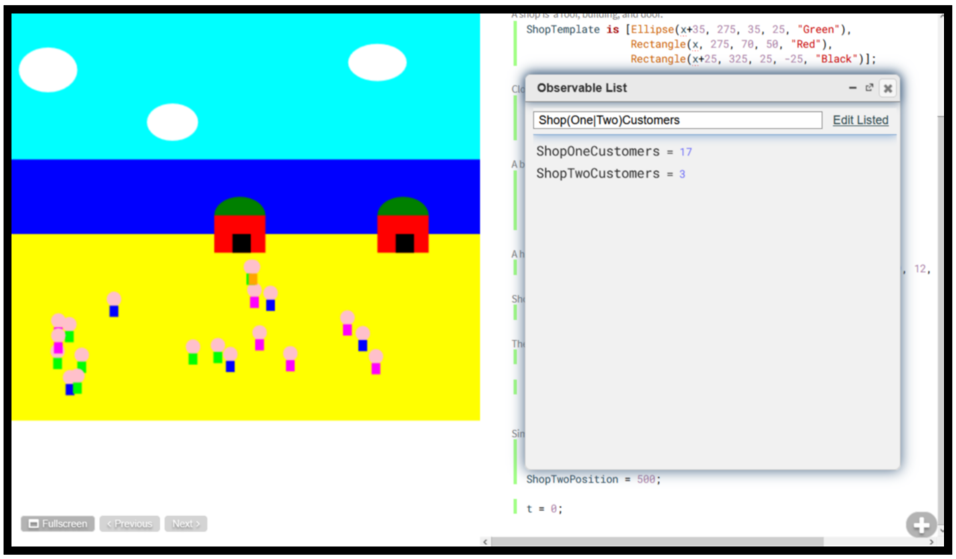

Figure 4.2.8: A shopkeeper takes advantage of the space

If the user moves a shop into the centre of the beach, such as in figure 4.2.8 it receives more business. In this case about two thirds of the customers. The other store can compete by also moving towards the centre, which can be modelled as follows. When both stores are in the centre, the customers are again split evenly between them. This new arrangement is stable because neither store benefits from moving and so they are encouraged to remain in place.

The main interface of the construal is a page which sets up the images and allows the user direct access to the shop position observables. There are also three scripts, which allow the user to generate customers, animate the customers travelling to their chosen store, and count the customers that each store receives.

The first section of code sets up the simulation and draws some graphics to the

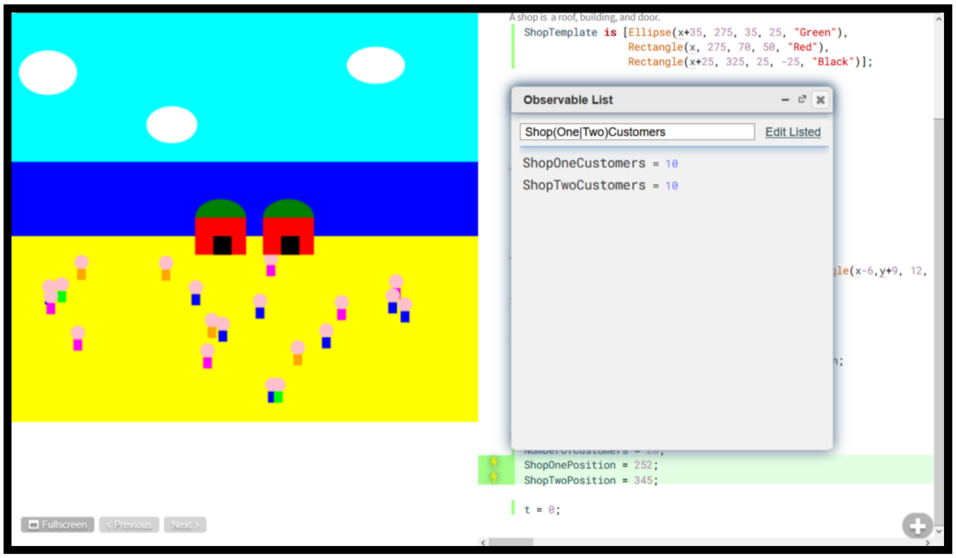

Figure 4.2.9: The other store moves to the centre, restoring balance

screen. There is nothing special about the graphics. The beach, shops, and sky consist of simple geometric shapes that are drawn in combination. The store positions are assigned a dependency to allow the user to move them easily. "With" statements are used to create two shops from the same graphical template, with the positions of each given by the x-coordinate observables defined later. Finally, some observables are declared to reflect basic features of the simulation: the positions of each shop, the number of customers on the beach, and the simulation time. The three scripts then allow the user to interact in ways that are thematic with the exploration of Holliday's Law.

The GenerateCustomers script uses a customer graphical template, consisting of a rectangular torso and circular head, and with statements to generate customers with random x and y positions across the beach. A list containing the closest shop to each customer is generated, which can be used to determine which store they will visit. As an aesthetic flourish, dependencies are used to model the customer's position as a function of time – allowing for an animation of customers travelling to their chosen store. The CountCustomers script can be used to count the number of customers that would visit each store. The script is interesting because it is entirely procedural; it does not make any use of observables or dependencies. There are methods of counting that use dependencies exclusively, but it is intuitive to think of counting as a procedural activity (consider one object and count it, then consider the next, et cetera).

Finally, the LunchTime script drives the animation of the customers as they travel to their destination. Since the customer position is a function of time, the script works by slowly increasing the simulation time from zero up to one hundred. As the simulation time progresses, the customer location dependency becomes closer to the target. This cascades upwards to the graphics representing the customer, causing them to move.

4.2.6 Bayesian Reasoning

Introduction

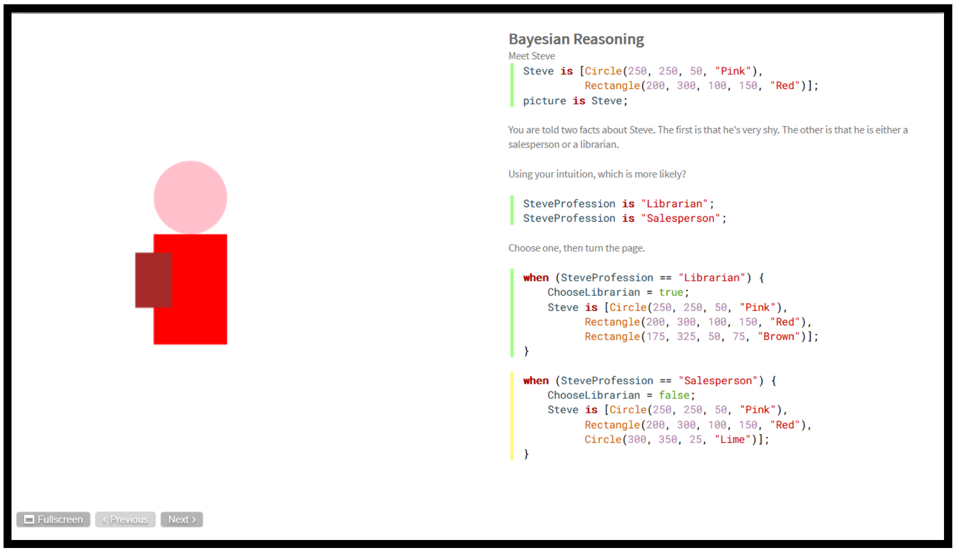

Figure 4.2.10: The Bayesian Reasoning Construal

Link: `https://jseden.dcs.warwick.ac.uk/construit/?q=:me&load=555&vid=14493&r=`

Bayesian reasoning is a construal in the academic areas of psychology and statistical reasoning. By modelling the underlying statistics, it addresses a common error in estimating the probability of an event. The construal benefits the report by showing how Empirical Modelling principles can be applied to education in a new academic area. The process of making the model helps a student to demonstrate their knowledge and observe where there may be gaps in their understanding. The reasoning error that the construal models is the "base rate fallacy", or "base rate neglect". First described by Daniel Kahneman and Amos Tversky, the base rate fallacy refers to the tendency of people to ignore general statistical trends in favour of specific evidence, such that their "intuitive predictions are essentially un-affected by considerations of prior probability" [30, p. 1]. The construal illustrates the effect using a scenario based on an example given by Daniel Kahneman in his book, “Thinking, Fast and Slow”[31].

Participants are introduced to Steve, who is portrayed as shy and introverted, then asked whether Steve is more likely to be a librarian or a salesperson. The overwhelming response is librarian since their preconceptions of the profession are closer to the personality profile of Steve. They are relying entirely on specific evidence. This conclusion is statistically incorrect since respondents are forgetting an important piece of information – there are twenty times more male farmers in the United States than male librarians. If a random man were chosen, there are significantly more likely to be a salesperson than a librarian. The additional information about the man’s character might make one outcome more likely, but the base rate is so skewed that Steve is still more likely to be a salesperson. The construal supports education from two perspectives. On one side, the creator refines their own understanding during the process. On another, any student can use the construal to gain insight into how the creator views the subject, which they can use to inform their own understanding. If there are aspects that the student does not accept, they can adapt the model to better fit their own experience.

Unlike previous construals, this construal consists of two separate activities which are performed in a specific sequence. First, the user is posed the question to encourage them to develop their own method for answering it. Then the user is run through the underlying statistics and shown a prediction method that accounts for the base rate. The user can use the model to try new probabilities to build an understanding of base rate neglect.

There are two observables to represent the base rate, one for each possibility: chance of salesperson and chance of librarian. The ratio is displayed graphically using rectangles, with the user able to change the two observables to visualise how a different base rate affects the probabilities, as demonstrated in 4.2.11. Clearly, the chance of Steve being a salesperson is far greater at this stage.

Next, two new observables are introduced to represent the information given about

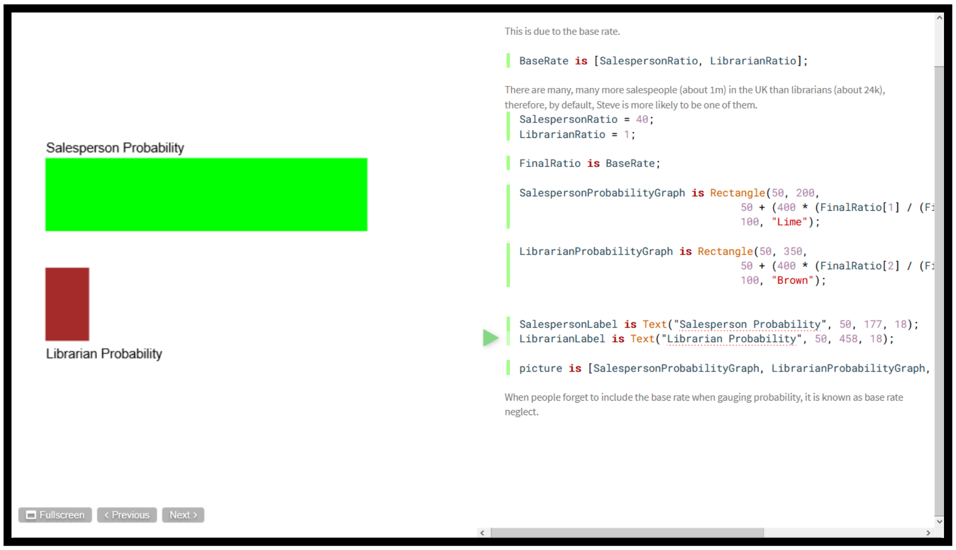

Figure 4.2.11: Bars demonstrating the base rate probabilties

Steve's personality. Together, the observables constitute the ratio implied by the new information. For example, if the user deems that a librarian is three times more likely to be shy than a salesperson, the observables will be a one for the salesperson and three for the librarian. The user can then incorporate this additional information by changing the observable "picture" to see how the probabilities change. This user can visualise how the new information should not overrule the base rate, as in 4.2.12.

Interestingly, the dependencies used by the construal are very simple. All four observables that represent probability are integers and the dependency for the resulting probability ratio only multiplies observables together. The simplicity of the idea when portrayed in this way raises the question of why base rate neglect is such a common error. Is it possible that, for most predictions of this type, the base rates are small and so do not affect the outcome? Are there benefits to base rate neglect in an evolutionary context? These observations arose in the process of creating the model, demonstrating that Empirical Modelling can lead the creator to new realisations about the topic by virtue of being able to review their present

Figure 4.2.12: Bars demonstrating the updated probabilities

understanding as a model.

4.2.7 Regular Expressions

Overview

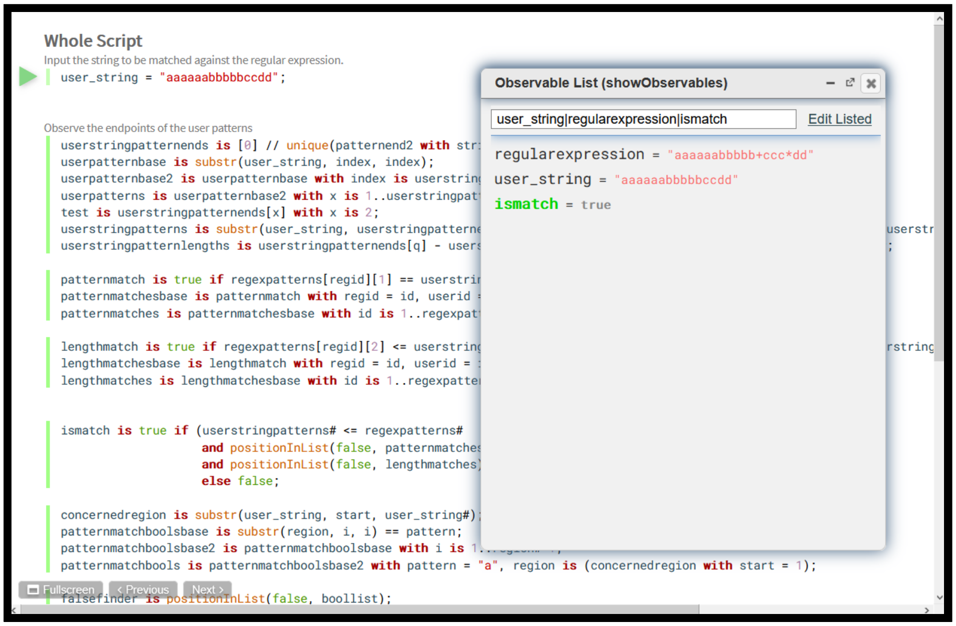

Figure 4.2.13: The Regular Expressions Construal

Link: `https://jseden.dcs.warwick.ac.uk/construit/?q=:me&load=559&vid=14604&r=`

This construal is concerned with deriving meaning from regular expressions, which are a tool from formal language theory designed to describe and recognize of languages. Each regular expression consists of a string of characters and operators that describe a set of strings that constitute a language. The construal is thematic for Empirical Modelling in that it aims to model how a human might make sense of the regular expression rather than formal methods of parsing. Regular expressions are a topic that is covered in the second year of the Computer Science course at the University of Warwick and a secondary purpose for choosing this subject is that it may discover interesting ideas relating to parsing that are not obvious when taught in the university course. This could illustrate the benefits of Empirical

Modelling for education.

The construal implements a small subset of the operations allowed by the regular expression grammars that are used in industry, but this suffices to illustrate the purpose of the construal. The operators supported are: “+” representing at least one instance of a character and “*” representing zero or more instances. For example, the regular expression “aa” matches a string containing two “a”s, whereas the regular expression “aa+” matches a string containing at least two “a”s.

The functional element of the construal consists of two input observables and an output observable, which allow the user to define a regular expression, a string to match against it, and then have the output observable reflect whether the given string matches the regular expression.

There are many different approaches to parsing a regular expression. One possibility is to use formal top-down or bottom-up parsing algorithms, an alternative is to generate a set of strings that match the regular expression then check if the target string is a member. Some have advantages in certain contexts which might dictate when they are used, but, in the context of Empirical Modelling, the especially interesting point is that even two approaches that are functionally identical might be preferred by different people. This implies that the choice of approach is personal, if a class of students were asked to create a model that represents how they would make sense of a regular expression, there is no guarantee that any of the models would be the same.

The construal is implemented to model how a human might determine whether a string is a member of the language of a regular expression. It begins by breaking the regular expression into a sequence of rules that describe the character that is expected at a given position in the string and the number of instances of that character that are expected. This is demonstrated in figure 4.2.14 with the rules given at the top of the observable list. In a fashion characteristic of Empirical Modelling, every stage of calculation refers to intuitive observations of some concrete feature of the model area.

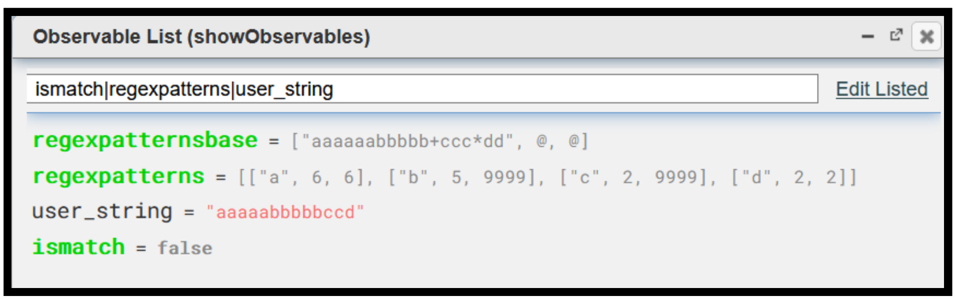

Figure 4.2.14: The rules behind a regular expression

Chapter 5

Final Analysis

5.1 Advantages

In the context of these examples, it is easier to understand what is meant by the open nature of Empirical Modelling. When the student first encounters a model that has been built by other people, or begins work on a model of their own, they are free to express their understanding however they choose. In the regular expressions construal, for instance, there are many potential implementations that are equally valid as opposed to more formal Computer Science in which there is great focus on formal models such as automata. The student can modify the functionality of the construal directly to better reflect their personal "mental model" or expand the model to demonstrate their developing comprehension of the topic. This is a useful proposition in education since it provides a window into the student's understanding of the meaning and function of a regular expression rather than their ability to manipulate them within conventional usage. In this way, Empirical Modelling is a good fit for the constructivist paradigm since it is flexible in its support of student knowledge construction, giving students freedom to express their experiential world, thereby allowing them to explore viable solutions in a way that is typically impossible.

The open nature of Empirical Modelling also has the advantage of extensibility. For instance, the ball throwing construal could be modified to account for air resistance or the ball rolling after hitting the ground. Construit! is especially effective at this type of expansion since the behaviour of models is not preconceived, the student is free to expand it as they desire. There is no need to design the construal from the beginning in such a way that expanding it requires radical rebuilding and the observable/dependency approach taken by Empirical Modelling makes adding new functionality simple since it can be built on top of previous observables. If the new behaviour requires new information about the model state, the user can define an observable to capture that feature. This is a valuable characteristic for Empirical Modelling since both instructionism and constructivism assert that complicated knowledge is built on simpler knowledge. As such, it is a common situation that the student will learn something new about a subject for which they have already developed a mental model.

Another example of the benefits of Empirical Modelling's openness is that models can be connected together. For instance, consider the DFA simulation and regular expression construal. A Computer Science student will learn that regular expressions and deterministic finite automata are equivalent in their expressive power. If a language can be represented by a regular expression, then it can also be represented by a DFA, and algorithms exist to convert between the two. If a student were to have build the DFA and regular expression construals separately, before learning about the connection between the two, they could subsequently connect the two construals. It is extremely thematic to do so within Empirical Modelling, since the act of combining construals is essentially deducing some connection between them in experience. The algorithmic relationship, or even an intuitive, informal relationship, can be expressed by using dependency to connect the ovservables within the two models. Thus, Empirical Modelling is well suited for drawing connections between different topics, which is important for the educational process.

Additionally, Construit! gives students the ability to control the cultural context of the construals they create in line with the UDL guidelines. On a visual level, the appearance of the construal can be altered, for example, the beach in beachside commerce can be changed to a high street or Martian colony. Construit! provides a great degree of freedom to do so since, unlike other approaches to educational technology where graphical options are limited to those that are pre-programmed, Construit! allows the user to manipulate the graphics in any way they deem meaningful. While this would not change the functionality of the program, the appearance is relevant to the construal's teaching effectiveness. Providing total freedom to customize the visual appearance in this way supports UDL guideline 7.2. Students are best able to understand the subject matter when it is presented in a way that is culturally familiar and/or aligns with their interests. This helps construals to engage students and nurture enthusiasm and interest in a given subject.

The construals encourage students to express understanding in form of relationships between observable features. By building the model up using a multitude of simple relationships that can be observed individually, it becomes easier for the student to understand how the model works because its complexity is built up from simple parts. Additionally, dependency relationships are a natural tool for exploring the connection between changing an element of the world state and seeing how it changes, which suits this type of problem where the aim is to observe how small changes affect the concept being modelled. While the graphical element of the construal links to cultural context to support student sense-making, it is also interesting that the graphical features are directly linked to the observables and dependencies that are stated in the program.

The informal approach of construals, in which capturing the student's understanding is more important than the rigour with which it is done, is unusual in theoretical computer science but has special value in an educational context. There is often an emphasis on formal methods of processing – such as regular expressions or finite automata in the field of language recognition, for good reason as these methods are necessary for practical application of the subject. The informal approach, however, has great value in education because it is much closer to the modes of thought that are actually employed by the students during the sense-making process. By this criteria, the regular expressions construal is a far more accurate model of student thought than a conventional implementation of a parser for regular expressions.

5.2 Limitations

While the practical component demonstrates many promising advantages of Empirical Modelling, the project also revealed challenges to be overcome if the Empirical Modelling approach is to become suitable for widespread usage.

A major problem is the reliance on a text-based programming language. Students may have never encountered programming before, which is as a barrier to engaging with Construit! Though Construal! programming could be considered more intuitive for a novice programmer due to being designed to reflect human thought processes and cognition, it is still an obstacle that must be overcome for the learning process to even begin. It has been noted that the use of programming languages in a classroom tends to shift focus to learning the tools rather than the subject matter. The difficulty associated with a programming language is compounded for more complex programs.

With complicated construals, some of the higher level dependencies can involve a deep and entangled web of other observables which can cause difficulty in understanding its purpose. Consider, for instance, the 'ismatch' observable in the regular expressions construal. It can be very difficult for a student to make sense of what the program is doing to solve the problem – even though each action, by the definition of Empirical Modelling, relates to some natural, observable feature of the problem. Therefore the accessible, human way that the construal represents the topic may not translate into improved student understanding.

Empirical Modelling also runs contrary to the most popular educational paradigm, instructionism, which is an obstacle to its widespread adoption. As demonstrated by the Kenya study [18], constructivist methods in the past have been met with scepticism by teachers, partly due to their novelty. There is no sign that Empirical Modelling is immune to this effect, in fact, evidence at this stage suggests otherwise. A study in a Thai secondary school mathematics class found that the student's first reaction to Empirical Modelling was negative due to a reluctance to learn a new tool, though fortunately this was overcome in time [5]. In order for Empirical Modelling to be integrated into classrooms, there is a struggle ahead to convince educators and students of its efficacy and to instill the confidence and competence required to use these new tools.

Finally, while Construit! supports many of the UDL guidelines, there are some that are lacking. For example guideline 1.3, which suggests offering alternatives to visual information, while Construit! is dominated by visual stimulus. Another guideline that is not well supported is 4.2, which concerns providing access to assistive technologies [21]. These are not mutually exclusive with the Empirical Modelling, which would be damaging because it would show that Empirical Modelling cannot be reconciled with every aspect of good educational technology. These weaknesses can be overcome by adding support for them in future updates to Construit! or by creating a new development environment that contains them from the beginning.

Chapter 6

Conclusions

In this report, the potential of Empirical Modelling to be an influential new paradigm for teaching was explored with reference to a wide variety of ideas, philosophies, and principles from modern educational theory. With a theoretical grounding, project work turned towards the production of practical examples of educational tools in the Empirical Modelling style to determine if the theoretical advantages can be observed in practice. As a result of these activities, the project found good reason to believe that Empirical Modelling has potential as a foundation for teaching tools in educational institutions.

In particular, Empirical Modelling's theoretical suitability based on the similarities between its philosophy and the educational paradigm known as constructivism is striking. Both philosophies begin with the assumption that knowledge is personal and subjective. In constructivism, the process of learning is characterised as building sensible conceptual structures to explain an entity's experiential world. Empirical Modelling is well suited to support this type of sense-making through its ability to model experience in the form of interactive artifacts that the user can manipulate to gain insight into the subject they are studying. Empirical Modelling has other advantages other over modelling approachs, such as the ease with which it can be updated and the fact that the modeller is not expected to fully understand the topic area before beginning to implement it. In this way, Empirical Modelling is a promising paradigm for constructivist education.

The Construit! environment for Empirical Modelling demonstrates that construals integrate many of the requirements that are outlined in CAST's Universal Design for Learning guidelines. In particular, those that concern engagement by making resources relevant to student experience and expression by giving students freedom to express their understanding. This demonstrates that there are inherent properties of Empirical Modelling that allow it to make for good educational resources.

There are obstacles for Empirical Modelling to overcome as well. There are some UDL guidelines that are not well supported by current Empirical Modelling tools as well as potential difficulty with convincing teachers of the value of the paradigm and training them to be comfortable with its usage. These problems can all be solved, however, so none of them is fatal to the future of Empirical Modelling as an educational tool.

Overall, Empirical Modelling is a promising candidate for the development of educational tools in the future and it is worthy of further research and development in this direction.

The project achieved all the core aims that were outlined at the beginning of the project, but there is still more that could have been done since the stretch goals were not fully completed. In terms of the theoretical component, it was an aim to study other forms of online, interactive resources which was not done due to time constraints, though it was possible to compare Empirical Modelling to some other paradigms due to the author's familiarity with them. With the practical component, the stretch goal of critiquing the features of Construit! was met, though introducing the environment to students for feedback was not performed due to a decision to focus on the core aspects of the project. Overall, the project is successful due to having met its aims and reaching a clear conclusion, however, there is more research to be done into this subject area.

Chapter 7

Further Research

A possible avenue of future inquiry is the use of Empirical Modelling for note taking. This report mostly considered how Empirical modelling could be used as a classroom tool for students to build up their understanding after being taught a subject, but it is reasonable to hypothesise that the same benefits would apply to note taking during class. Perhaps a student could build a construal that develops as new material is taught each lesson. The idea could even be extended by linking models together to show the relationships between the different topics that are covered in the subject. It would be interesting to study if this approach improved student outcomes, and teacher feedback would be useful for determining what adjustments might be necessary for the environment to see use in schools.

Another interesting application of Empirical Modelling could be to resolve a key limitation of constructivism, assessment. The subjective nature of knowledge in constructivism makes devising assessment methods difficult because there is no simple method for deciding ‘correctness’. Empirical Modelling could potentially be used as an assessment tool, with students asked to ‘answer’ a question by either creating a model of the topic or manipulating one that they are given. This could be a valuable contribution to the constructivist teaching paradigm.

For an especially practical project, somebody could attempt to build a new environment for developing construals that accounts for some of the weaknesses that have been outlined in this report.

A less technical project in Empirical Modelling could be to research ways of introducing Empirical Modelling tools and techniques into the classroom. The scepticism with which constructivist tools are treated is a significant barrier to its widespread adoption and requires just as much consideration as the technical challenges that the project faces.

Chapter 8

Author's Assessment

The main contribution of this project to Empirical Modelling is on a theoretical level. It combines together many aspects of theory and practice to produce a detailed insight into how Empirical Modelling can be applied to education. This multifaceted exploration of Empirical Modelling in the context of modern educational understanding constitutes a broader analysis than any other of which the author is aware. This is important for determing in Empirical Modelling should be pursued further as an educational paradigm since demonstrating its suitability with reference to a wide range of contemporary issues in the learning sciences

This project also contributes to Empirical Modelling on a technical level. The construals that were created during the practical component joins the range of interesting projects that are available via the Construit! website. In particular, some interesting ideas relating to Empirical Modelling were uncovered over the course of the project, such as the conceptual structures that arise when modelling regular expressions in experiential terms. Third year project students have always contributed to the practical demonstrations of Empirical Modelling since the field began with ARCA and this report is a continuation of that trend.

The contribution that this project makes to Computer Science more generally is a continuation of the paradigmatic argument that Empirical Modelling has always made. There is a common trend in Computer Science, and mathematics more broadly, to assume that the way to truth is rigorous formality, but it is interesting to consider when goals might be better pursued through a more informal approach. The experience driven approach of Empirical Modelling is concerned with ideas that are often seen as outside the remit of conventional Computer Science, it offers some insight into the nature of human reasoning and knowledge and how computers can support their development on a fundamental level.

The difficulties associated with 'proving' the effectiveness of an educational technique satisfactorily made such an endeavour far beyond the scope of this project due to difficulties in evaluative research in this field. Measuring the effectiveness of a learning paradigm requires study over a long period of time due to the reliance on long-term outcomes to form a meaningful evaluation, which was not realistic within the timeframe of this project. A further issue is in the difficulty of gaining access to a teacher and classroom to even begin such an experiment, compounded by global disruption in the education sector caused by the Covid-19 pandemic which was in full effect throughout the project. In this sense, the project is limited as its findings are not of immediate practical value. The project does, however, serve as a foundation for further research in this area by illustrating the advantages that Empirical Modelling may be able to offer the educational technology industry.

Another limitation is one of interpretation. Philosophies rooted in subjectivity and experience can be understood differently by different people due to their different experiences and beliefs. In this sense, the project may suffer from the same issues as constructivism in that there are many different interpretations of the epistemological issues that are raised [20]. A wider audience may not find the version of Empirical Modelling that is portrayed here to be particularly compelling since it is the viewpoint of the author. In Computer Science, where mathematical proofs are so prevalent, it is rare to encounter epistemological questions such as these. Nonetheless, hopefully this report makes the argument for their importance since they are at the core of Empirical Modelling at the potential that it offers.

Chapter 9

Acknowledgements

The author would like to thank Jonathan Foss and Meurig Beynon. Without their selfless dedication of time and willingness to impart their experience, this project would have been much harder and not nearly so interesting to carry out. As it is, they have inspired an interest in the role of epistemology in computing that will last a very long time.

Chapter 10

Glossary

There is a set of vocabulary associated with empirical modelling that a reader may not have experience with. This glossary is provided for reference.

Construal: A model created in accordance with the Empirical Modelling paradigm

Constructivism: A philosophy of education based on the idea that knowledge in a meaningful form exists only in the mind of an agent. A learner focused paradigm that emphasises the nature of understanding as being "constructed" on previous knowledge.

Definitive Notation: A notation designed to represent the observable definitions that constitute Empirical Modelling.

Construit!: A development environment for the JSEden language, which is based on the empirical modelling philosophy.

Dependency: A perceived relationship between two observables in a construal.

Empirical Modelling: A modelling methodology aimed at representing the human understanding of a given topic. Results in open, experiential models rather than complete, mathematically rigorous ones.

Instructionism (Standard Model): A philosophy of education predicated on the existence of an external world that can be known. The emphasis in this approach is on the teacher efficiently and accurately transmitting their understanding of the subject to the learners.

Model Viability: A measure of correctness that accounts for subjectivity in human experience. A mental model is viable if it is satisfactory for the experiential world in which it was developed.

Observable: An Empirical Modelling construct that refers to a feature in the modeller's experience.

References

[1] M. Nathan and R. Sawyer. Foundations of the learning sciences. In R. Sawyer, editor, *The Cambridge Handbook of the Learning Sciences*, pages 21–43. Cambridge: Cambridge University Press, 2014.

[2] Department for Education. Schools, colleges, and early years settings to close [online]. Available from: https://www.gov.uk/government/news/schools-colleges-and-early-years-settings-to-close. Accessed: 2021 April 26.

[3] N.M. Seel. History of the sciences of learning. In N.M. Seel, editor, *Encyclopedia of the Sciences of Learning*. Boston, MA: Springer, 2012. https://doi.org/10.1007/978-1-4419-1428-6_916.

[4] A. Harfield, R. Alimisi, P. Tomcsanyi, N. Pope, and M. Beynon. Constructionism as making construals: First steps with js-eden in the classroom. In *Constructionism in Action*, pages 42–52. Thailand: Suksapattana Foundation, February 2016.

[5] A. Harfield and M. Beynon. Empirical modelling for constructionist learning in a thai secondary school mathematics class. In *International Conference on eLearning for Knowledge-Based Society*, pages 13–14, December 2012.

[6] OECD. Employment rates of 25-64 year-olds, by educational attainment (2019): Percentage of employed 25-64 year-olds among all 25-64 year-olds. In *The Output of Educational Institutions and the Impact of Learning*. Paris: OECD Publishing, 2019.

[7] OECD. What are the earnings advantages from education? In *Education at a Glance 2020*. Paris: OECD Publishing, 2020.

[8] OECD (2017). *Getting Skills Right: Good Practice in Adapting to Changing Skills Needs: A Perspective on France, Italy, Spain, South Africa and the United Kingdom*. Paris: OECD Publishing, 2017. Available at: `http://dx.doi.org/10.1787/9789264277892-en`.

[9] D.R. Garrison. From independence to collaboration: A personal retrospective on distance education. In M. Cleveland-Innes and D.R. Garrison, editors, *An Introduction to Distance Education: Understanding Teaching and Learning in a New Era*, pages 13–24. New York, NY: Routledge, 2021.

[10] NCES. Distance learning [online]. Available from: `https://nces.ed.gov/fastfacts/display.asp?id=80`. Accessed: 2021 April 24.

[11] M. Sadeghi. A shift from classroom to distance learning: Advantages and limitations. *International Journal of Research in English Education*, 4(1): 80–88, 2019.

[12] Khan Academy. Why khan academy works. Available from: `https://www.khanacademy.org/`, 2021. Accessed: 2021 May 10.

[13] E. Von Glasersfeld. An introduction to radical constructivism. In P. Watzlawick, editor, *The Invented Reality*, pages 17–40. New York: Norton, 1984.

[14] M.G. Johnson. Instructionism and constructivism: Reconciling two very good ideas. *International Journal of Special Education*, 24(3):90–98, 2009.

[15] Y.B. Kafai. Playing and making games for learning: Instructionist and constructionist perspectives for game studies. *Games and Culture*, 1(1):36–40, 2006.

[16] A. Albirini. The crisis of educational technology, and the prospect of reinventing education. *Educational Technology & Society*, 10(1):227–236, 2007.

[17] E. Von Glasersfeld. A constructivist approach to teaching. In L.P. Steffe and J. Gale, editors, *Constructivism in Education*, pages 3–15. Erlbaum, Hillsdale, 1995.

[18] G. Mwanda and R. Midigo. Understanding the bottlenecks in methodological adoption of constructivism in secondary schools in kenya. *Jurnal Pendidikan Biologi Indonesia*, 5(1):141–150, 2019.

[19] L.K.S. Abiatal and G.R. Howard. Constructivism-led assistive technology: An experiment at a namibian special primary school. *South African Journal of Childhood Education*, 10(1), 2020.

[20] E. Murphy. *Constructivism: From Philosophy to Practice*. 1997.

[21] CAST. Universal design for learning guidelines version 2.2. Available from: `https://udlguidelines.cast.org/`, 2018. Accessed: 2021 May 10.

[22] CAST. About cast. Available from: `https://www.cast.org/about/about-cast`, 2021. Accessed: 2021 May 10.

[23] E.L. Higgins and M.H. Raskind. Compensatory effectiveness of speech recognition on the written composition performance of postsecondary students with learning disabilities. *Learning Disability Quarterly*, 18(2):159–174, 1995.

[24] M. Beynon and H. Zhu. Constructivist computing - a new paradigm for open and distance learning? In *Proceedings of the 25th ICDE World Conference*. Tianjin, China, October 2013.

[25] W. James. *Essays in Radical Empiricism*. Raleigh, NC: Alex Catalogue, 2001.

[26] B.J. Thayer-Bacon. Exploring william james's radical empiricism and relational ontologies for alternative possibilities in education. *Studies in Philosophy and Education*, 36(3):299–314, 2017.

[27] W.M. Beynon. Radical empiricism, empirical modelling, and the nature of knowing. *Cognitive Technologies and the Pragmatics of Cognition*, 18(2): 159–174, 2005.

[28] Construit! Partners. About construit! Available from: `http://construit.org/project/about/`. Accessed: 2021 May 10.

[29] Oxford Reference. Hotelling's law [online]. Available from: `https://www.oxfordreference.com/view/10.1093/oi/authority.20110803095946276`, 2021. Accessed: 2021 May 10.

[30] D. Kahneman and A. Tversky. On the psychology of prediction. *Psychological Review*, 80:237–251, 1973.

[31] D. Kahneman. *Thinking, Fast and Slow*. New York: Farrar, Straus and Giroux, 2011.