Learning about Black Holes and how to Observe them by Constructing a Qualitative Model – A Pilot study

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Abstract

This paper describes a qualitative reference model developed to support students in learning about black holes. The model explains the factors that play a role when astronomers want to create an image of a black hole. An important step in creating such a reference model is decomposing the model into a progressive series of self-contained units (runnable partial models) that collectively form the complete model. Each unit has explicit learning objectives targeting both domain knowledge and systems thinking, with the complexity of these objectives gradually increasing throughout the lesson. A pilot study involving 13 secondary school students was conducted to evaluate the lesson. The results show that students can construct the intended model when supported by the scaffolds provided in the software. The pre- and post-test results indicate improvements in both domain knowledge and systems thinking. In the open question, students identified a larger number of relevant properties influencing the observation of a black hole after completing the lesson, although they rarely articulated the causal relationships between these properties. The findings suggest that qualitative modelling can support students in learning about the mechanisms underlying black hole imaging and offer directions for further refinement and evaluation of the lesson.

1 Introduction

Learning about dynamic systems by creating models is a valuable way of learning [1], especially when creating qualitative models [2,3]. However, learning through modelling is a challenge [4], even when using qualitative models. To address this challenge, we have developed an approach that helps students to achieve their learning goals in a step-by-step manner [5]. Reference models form a key component of this approach [6,7,8]. They are used to automatically generate support and feedback required by students to successfully build their model.

The work presented in this paper is based on a reference model that explains how astronomers create an image of a black hole. Astronomy is known to be one of the most interesting and motivational science fields for both boys and girls [9,10], with black holes being some of the most fascinating objects in the universe. Black holes are also of recent scientific interest, including the first images of black holes [11,12] and the detection of gravitational waves [13].

A key feature of a reference model is its decomposition into meaningful learning units. To achieve this, we adhere to previously established requirements [14]: (*i*) each unit should be a self-contained and manageable model, (*ii*) each unit should address at least one meaningful aspect of the subject matter, (*iii*) units should be organised in a step-by-step progression sequence, and (*iv*) units should be engaging and curiosity driven.

To assess how students work and learn with the lesson built around this reference model, a small pilot study was conducted in a classroom setting with pre-university physics students. The findings of this study are also reported in this paper.

The content of the paper is organised as follows. Section 2 summarizes the subject matter. Sections 3 and 4 describe the modelling software and its support functions. Section 5 presents the complete reference model, and the self-contained units. Section 6 describes the results obtained from the pilot study. Section 7 concludes the paper.

2 Black holes

A black hole is a dense object with a gravitational pull exceeding the speed of light; once matter or light crosses the event horizon, nothing can escape. Small, or stellar-mass, black holes ($M \sim 10\text{-}100 M_{Sun}$) are the remnants of massive stars which have collapsed under their own gravity at the end of their lives, and can be found throughout galaxies, including the Milky Way.

Another group of black holes are much more massive, reaching billions of solar masses. These supermassive black holes are only found at the centres of galaxies. The supermassive black hole at the centre of the Milky Way galaxy (Sagittarius A*) is approximately 4 billion times the mass of the Sun. How these supermassive black holes formed is not known, but it is thought that they grow and evolve together with their host galaxy.

Black holes do not emit light, so we cannot observe them directly. However, supermassive black holes are typically surrounded by a hot, glowing disc of gas and dust (the accretion disc) which is spiralling into the black hole and will eventually be consumed by it. The accretion disc can emit an enormous amount of light, sometimes enough to outshine an entire galaxy. The light from the accretion disc has enabled scientists to image the shadow of a black hole, both in the centre of our own galaxy and in the galaxy M87, using a global network of telescopes [11,12] (Fig. 1 and 2).

The visibility of a black hole's shadow in an image depends on several factors. Firstly, the mass of the black hole determines its physical size – the larger the radius of the black hole, the larger the shadow. Secondly, the distance between the observer and the black hole – the further away from the observer the black hole is, the smaller its shadow will appear. As such, the supermassive black hole in M87, which is approximately a factor of 1000 more massive than Sagittarius A* (the black hole in the centre of our Milky Way galaxy), is also approximately 1000 times further away, meaning that both black holes appear to have a similar size on the sky for the observer (see Fig. 2). Thirdly, the rate at which a black hole is consuming its accretion disc (the accretion rate) determines how much energy is emitted by the disc – the brighter the disc, the easier it will be to observe the shadow. Fourth, black holes rotate on their axes (spin of the black hole). This 'spin' effects the accretion disc, which can cause deformation in the disc, and in the image ('lumpy' ring of light).

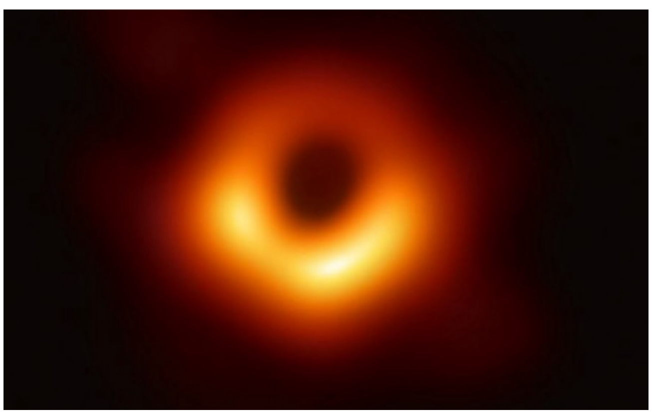

Fig. 1. Image of the black hole at the centre of the Milky Way, taken by the Event Horizon Telescope (image credit: EHT).

Finally, the properties of the telescope used to observe the black hole also play an important role. A telescope with a larger diameter can observe fainter objects, enabling astronomers to observe bright objects which are further away from Earth or objects which emit less light. Furthermore, the combination of the telescope size and the wavelength of the light observed influences how easily a telescope can resolve two objects close together on the sky (resolving power). To observe the two black holes, M87* and Sagittarius A*, the Event Horizon Telescope (EHT) collaboration used a network of radio telescopes across the world to create a virtual telescope the size of the Earth [11,12].

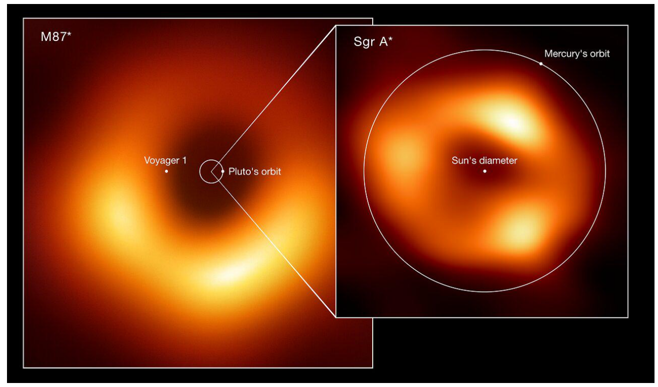

Fig. 2. Size comparison of two black holes imaged by the Event Horizon Telescope (image credit: EHT).

3 Qualitative reasoning with DynaLearn

DynaLearn (https://www.dynalearn.nl) is an interactive application in which students create and simulate qualitative models. The software can be used at different levels of complexity [15]. The reference model 'Image of a black hole' has been created at level 2.

At level 2, the following ingredient types be used to create representations. *Entities* are physical objects and/or abstract concepts in the system, e.g. the radio telescope. *Configurations* represent structural relationships between entities, e.g. the image contains a ring. *Quantities* are changeable and measurable features of entities, e.g. mass. At level 2, quantities only have a *Direction of change* (∂), which can be decreasing, steady or increasing. *Causal dependencies* are directed relationships between quantities specifying how the change of one quantity influences the change of another. They can be positive, e.g., a increasing accretion rate results in a brighter ring, or negative, e.g., when the distance increases, the visibility decreases.

When simulating a model, the initial direction of change must be defined for quantities at the beginning of the causal path(s). A simulation results in a *State-graph*, which can consist of one or more *States* and *Transitions. States* are unique qualitative behaviours of the system and *Transitions* show continuous passages between pairs of states.

4 Support functions in DynaLearn

Various forms of automated support have been developed to provide students with feedback and guidance [5].

Norm-based advice (Fig. 3). Each time students create something in the model, their work is compared to the underlying reference model. Discrepancies are flagged by the appearance of a question mark. If a student clicks on or hovers over the question mark, advice appears regarding possible mistakes in the model. However, it is up to the student to find solutions for the highlighted problems.

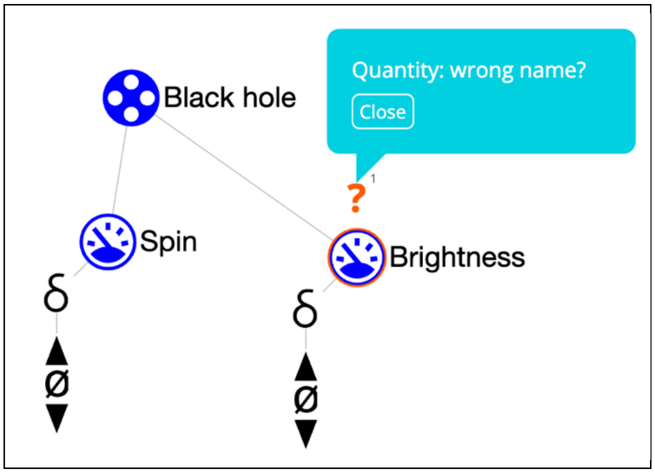

Fig. 3. Norm-based advice (Quantity: Wrong name?).

Scenario advice (Fig. 4). Every time the model is simulated, checks are made for missing information and inconsistencies provided to the qualitative reasoning engine. Errors are signalled by an exclamation mark; students can click on this symbol or hover it for support. Fig. 4 shows an example in which the initial change is missing. Scenario advice also identifies and highlights feedback loops.

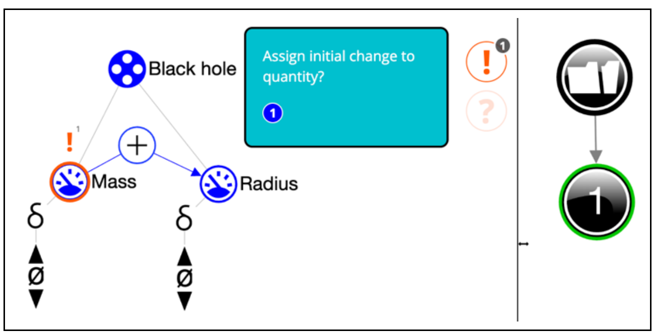

Fig. 4. Scenario advice (Assign initial change to quantity?).

Progress bar (Fig 5). Students can monitor their progress using the progress bar. Each ingredient type is shown alongside (*i*) total number to be created (e.g., 7 entities and 12 quantities), (*ii*) number created correctly (e.g., 1 entity and 2 quantities), and (*iii*) number created incorrectly (e.g., 0 entities and 1 quantity). When all ingredients have been correctly created, the numbers become green; incorrect ingredients are shown in red.

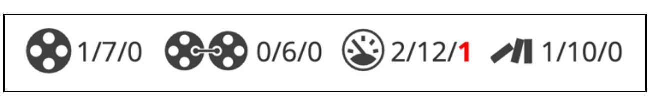

Fig. 5. Progress bar (showing a selection to maintain readability).

Short **instruction videos** ('how-to create') are continuously available for each ingredient type. Furthermore, lessons are accompanied by a workbook which provides short explanations of the phenomenon (text and visuals) and of the ingredients that form the qualitative vocabulary. The workbook leads the student through the sequence of units, supporting the creation of the model using a step-by-step approach (see https://dynalearn.nl/#lessons for examples).

5 The Model

The full model, including evaluation and refinement, was made in collaboration with domain experts. The resulting model is shown in Fig. 6. The model is built at level 2 of the software, which is relatively simple for students in secondary education. However, the complexity of this model arises from the number of ingredients and connections to be created (35 modelling steps), combined with several intermediate simulation steps using a variety of initial values.

When running the model with the initial settings as shown in Fig. 6, the simulation generates nine distinct states of behaviour (Table 1), mainly as a result of ambiguity in the model. The ambiguity arises from the competing influences on *Brightness* and *Visibility*. In this case, *Brightness* is negatively influenced by *Deformation*, but at the same time, *Deformation* is decreasing, which results in increasing *Brightness.* In addition, *Brightness* is positively influenced by *Accretion rate*, which itself is decreasing, causing *Brightness* to decrease. This leads to an ambiguity for *Brightness*, which can thus be decreasing, steady or increasing.

A similar situation holds for *Visibility*, which is opposingly influenced by *Distance* and *Resolving power*, and thus also ambiguous. Hence, *Brightness* and *Visibility* each have three possible behaviours, which results in a state-graph with nine states in total (Table 1). Note that *Resolving power* itself is unambiguous. Indeed, it has opposing influences, but the two influencing quantities move in opposite directions.

The full model has been decomposed into three units. The first unit focusses on the key quantities of the black hole. In the second unit, students turn their attention to the accretion disc. The third and final unit addresses the quantities that characterise the radio telescope. These units are discussed in the next subsections.

5.1 Characteristics of a black hole

The learning objectives in this section are (*i*) to understand how the mass of a galaxy and the distance to the observer affect the visibility of a black hole's shadow, and (*ii*) to reason about simple causal chains.

The workbook starts with a text explaining which properties of the black hole influence the visibility of the shadow of the black hole in the image, followed by instructions for constructing this part of the model (Fig. 7).

Students first create the entities *Galaxy* and *Black hole*, connecting them with the configuration *in centre of.* Subsequently, the quantities *Mass* (of the galaxy) and *Mass* (of the black hole) are added, as well as the causal dependency between these quantities. The type (+ or -) and direction of the causal relationship is not given; students must identify this based on the available text. Norm-based feedback supports students during this and subsequent construction steps.

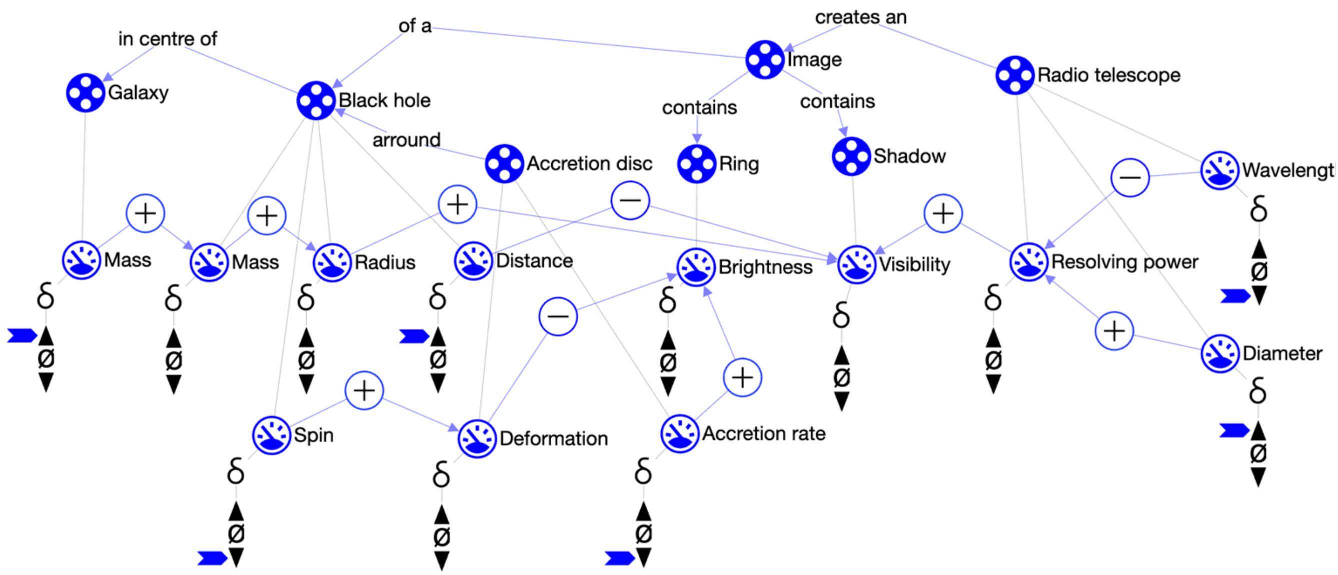

Fig. 6. Qualitative model – Image of a black hole. There are six initial changes, namely *Mass* (Galaxy), *Distance* (Accretion disc), and *Diameter* (Radio telescope) increase, while *Spin* (Black hole), *Accretion rate* (Accretion disc) and *Wavelength* (Radio telescope) decrease.

Table 1. Simulation results for the 'Image of a black hole' model shown in Fig. 6. S refers to State and the subscript to the state number.

Entity	Quantity	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9
Accretion disc	Accretion rate	-	-	-	-	-	-	-	-	-
	Deformation	-	-	-	-	-	-	-	-	-
Black hole	Distance	+	+	+	+	+	+	+	+	+
	Mass	+	+	+	+	+	+	+	+	+
	Radius	+	+	+	+	+	+	+	+	+
	Spin	-	-	-	-	-	-	-	-	-
Galaxy	Mass	+	+	+	+	+	+	+	+	+
Radio telescope	Diameter	-	-	-	-	-	-	-	-	-
	Resolving power	+	+	+	+	+	+	+	+	+
	Wavelength	-	-	-	-	-	-	-	-	-
Ring	Brightness	-	-	-	0	0	0	+	+	+
Shadow	Visibility	-	0	+	-	0	+	-	0	+

The initial change for the *Mass* (of the galaxy) is then set to increase, and students are instructed to run the first simulation (Fig. 7). With targeted reflection questions in the workbook, such as 'When the mass of the galaxy increases, the mass of the black hole *decreases / remains the same / increases'*, students reflect on the simulation outcome.

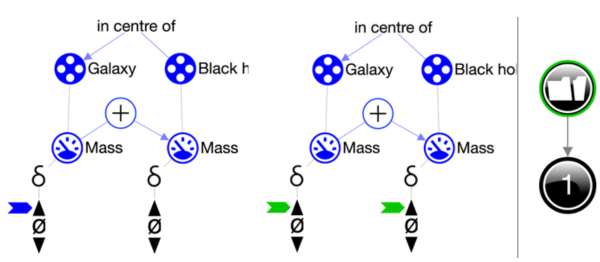

Fig. 7. The first part of the model. On the left-hand side the initial change for *Mass* (Galaxy) is set to increase. The simulation result on the right-hand side shows that *Mass* (Black hole) is now also increasing.

Next, students expand the model with the entities *Image* and *Shadow* (Fig. 8). They add configurations between these entities and the entity *Black hole* to represent that there is an *Image of a Black hole* and the *Image contains a Shadow.* Students then add the quantities *Radius* and *Distance* to the entity *Black hole* and the quantity *Visibility* to the entity *Shadow*. Students are then asked to think about which causal dependencies should be created between the newly added quantities and previously created quantities.

During the simulation phase, students are instructed to set the initial change for *Mass* (of the galaxy) to increasing and set the initial change for *Distance* to steady, which simulates the situation in which a larger black hole is observed, albeit from an equal distance from the observer (Fig. 8).

The students are then asked to reflect on the simulation result using reflection questions: 'If we look at galaxies with increasing masses, the mass of the associated black holes will *decrease / remain the same / increase.* As a result, the radius of the black hole will *decrease / remain the same / increase.'*

'If the distance to the observer remains the same, the size of the shadow in the image will *decrease / remain the same / increase.'* Students must then adjust the initial changes before simulating the model again, to analyse the influence of a changing distance relative to the observer while the mass of the galaxy remains steady.

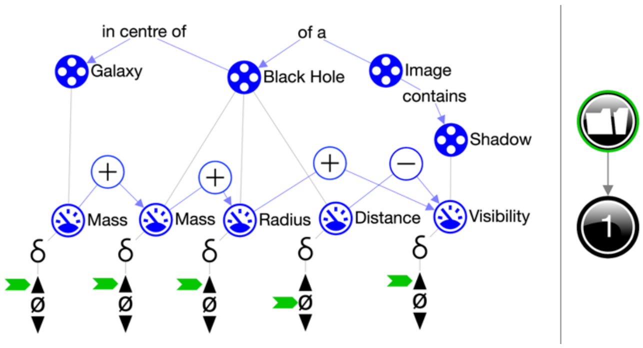

Fig. 8. Model of how an increasing *Mass* (Galaxy) and a steady *Distance* (Black hole) to the observer leads to an increasing *Visibility* (Shadow) of the black hole in the image.

5.2 Characteristics of the accretion disc

In the second part of the lesson, the learning objectives are (*i*) to understand how black hole spin and accretion rate affect the brightness of the accretion disk in an image, and (*ii*) to reason about ambiguous system behaviour resulting from competing causal influences. The part starts with a text that informs students about how the properties of the accretion disk and the spin of the black hole affect (homogenous) brightness of the ring in the image of the black hole.

Students must now add the entities *Accretion disc* and *Ring* to the model. Configurations are added to represent how these new entities are connected to the already existing entities: The *Accretion disc* is *around* the *Black hole* and the *Image contains* a *Ring.* After this, students are required to add four new quantities (*Spin, Deformation, Accretion rate* and *Brightness*). They must themselves identify the entities to which these quantities belong using the accompanying text. In the final construction step of this phase, students are again asked to think about the causality and create three causal dependencies between these newly added quantities.

For the simulation, the initial change for both the *Spin* (of the black hole) and the *Accretion rate* (of the accretion disc) are set to increase. Because the increasing deformation of the black hole has a negative influence on brightness and the increasing accretion rate has a positive influence on the brightness, two opposing influences act on the brightness of the ring. The magnitude of these changes is unknown, so three possible outcomes may occur: the brightness can decrease, remain the same or increase (Fig. 9). Students analyse each of the outcomes using the following reflection statements: 'The brightness of the ring in the image *decreases / remains the same / increases*. This is because the influence of the increasing accretion rate is *smaller than / equal to / greater than* the influence of the increasing spin of the black hole.'

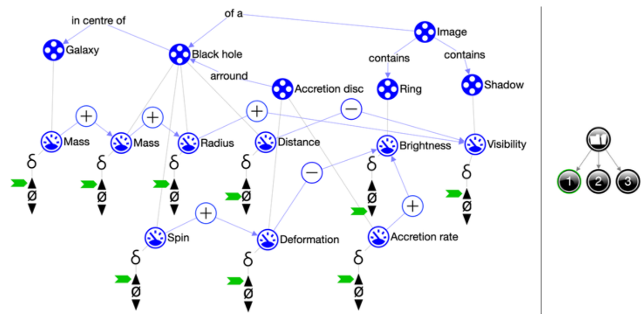

Fig. 9. Model of how an increasing *Accretion rate* (Accretion disc) and *Accretion spin* (Black hole) lead to an ambiguous simulation outcome for *Brightness* (Ring).

5.3 Characteristics of the radio telescope

In the final part of the lesson, the learning objectives are (*i*) to understand how the properties of a radio telescope affect the visibility of the black hole shadow in the image, and (*ii*) to predict and explain complex ambiguous system behaviour involving multiple interacting causal dependencies.

Students study a text about the characteristics of the radio telescope before adding the entity *Radio telescope,* and the configuration *creates an* between *Radio telescope* and *Image,* to their model. Next, three new quantities (*Wavelength*, *Diameter* and *Resolving power*) are added to the entity *Radio telescope*, which students must identify themselves from the accompanying text. Finally, students are asked to think about causality and construct the required causal dependencies between the new quantities and the other quantities already in the model.

Before running a simulation, students are asked to explain which quantities of the telescope influence the visibility of the shadow in the image. They then reason about how the initial values should be set to increase the visibility of the shadow. After formulating their predictions, students set the corresponding initial changes and run the simulation. In this assignment, the simulation outcome provides direct feedback on the correctness of their chosen initial values.

For the final simulation, the initial values are set as shown in Fig. 6. In this situation, multiple influences simultaneously affect both the *Brightness* (of the ring) and the *Visibility* (of the shadow), resulting in ambiguous simulation outcomes for both quantities. Before running the simulation, students are asked to predict how many possible states they expect the simulation to generate. They then run the simulation, which produces nine possible states, caused by three ambiguous outcomes for *Brightness* (of the ring) (decrease, remain the same and increase) and three ambiguous outcomes for the *Visibility* (of the shadow).

Using targeted reflection questions in which incorrect alternatives must be crossed out, students reason about the arising of the nine states and reflect on their predictions.

6 Evaluation study

The developed lesson was piloted in a grade 11 secondary school physics class comprising 13 students in preparation for a larger-scale study. These students had not had a lesson about black holes before. They had previously worked once with qualitative modelling using DynaLearn. During the pilot study, students were given 80 minutes to construct the model. The study addressed the following research questions:

- To what extent are students able to construct the correct model?
- To what extent does constructing the model contribute to system thinking and to domain knowledge concerning how scientists observe black holes?

6.1 Methodology

6.1.1 Construction process

During the construction of the model, all modelling actions were logged within the software. The analysis focused on the number of correctly constructed modelling ingredients and the frequency with which students used the support functions (norm-based support, scenario advice and video support). These data were used to answer the first research question concerning students' ability to construct the model correctly.

6.1.2 Pre- and post-test

To answer the second research question, pre- and post-tests were used to evaluate the students' progress on (*i*) system thinking and (*ii*) domain knowledge. The system thinking part consisted of six multiple-choice and multiple-response questions (Table 2). To minimize the influence of domain knowledge, simple contexts were used. For example, the fourth item required students to select the representation that correctly described the effect of applying force to a ball on the velocity of that ball. This system consisted of two entities (arm and ball), two quantities (force and velocity), and one causal relationship (force affects velocity). In the sixth item, students were presented with a simulation result of a model concerning poverty. The model comprised a causal chain with three entities and two causal relationships: poverty in a country positively influences food shortage among the population, which negatively affects the number of births. The simulation showed what happens when poverty decreases. Students were asked to interpret the simulation result and select the corresponding answer.

Table 2. Pre- and post-test items on system thinking (MR = multiple-response and MC = multiple-choice).

Question	Answer type
What is an entity?	MR
What is a quantity?	MR
What is a causal relationship?	MR
What is a system?	MC
Propagation in a causal chain	MR
Simulation results	MC

The second part of the test focused on the domain knowledge concerning how an image of a black hole is created. Students first answered the open question: *'Explain step-by-step which quantities of the black hole and the telescope influence how we observe the black hole in an image.'* This was followed by nine multiple-choice questions focusing on the causal relationships between the quantities that influence how the black hole is observed in an image:

- black hole mass and black hole radius;
- black hole radius and visibility of the shadow in the image;
- black hole spin and deformation of the accretion disc;
- deformation of the accretion disc and homogeneous brightness of the ring in the image;
- accretion rate of the accretion disc and brightness of the ring in the image;
- wavelength of telescope and resolving power of the telescope;
- telescope diameter and resolving power of the telescope;
- resolving power of the telescope and visibility of the shadow in the image.

Students could not return to the open question while answering the multiple-choice questions to avoid answers being adjusted.

6.1.3 Scoring

The score for the multiple-response items was calculated as correct minus incorrect answers and subsequently normalized to a value between 0 and 1. Multiple-choice items were scored as 1 if answered correctly. The first part of the test had a maximum score of 6, while the second part had a maximum score of 9.

Responses to the open question were analysed based on the number of correctly identified quantities and causal relationships influencing how the black hole is observed. Answers were categorized into four groups:

- properties of the black hole;
- properties of the accretion disc;
- properties of the telescope;
- properties of the image.

For example, a response mentioning the influence of black hole mass was categorized under *properties of the black hole*. This categorization was used to compare differences between students' pre- and post-test responses.

6.2 Results

6.2.1 Construction process

Table 3 summarizes the number of correct modelling ingredients students were able to construct within 80 minutes. Three students were able to complete the entire model within the allotted time. Four students completed the part concerning the properties of the accretion disc but did not reach the final section in which the telescope properties were incorporated into the model. The remaining six students started the telescope section but were unable to complete it within the available time. For example, these students had already read the accompanying text and constructed the entities and/or quantities in the model, but they did not reach the stage of constructing the causal relationships between the quantities and run the final simulations.

Table 3. Summary correct ingredients and support use.

Measure	M	SD
Correct ingredients (total=35)	30	3.2
Pop-ups norm-based support	93	34
Clicks norm-based support	1,0	2,3
Videos support	2.4	3.9
Scenario advice	0.8	1.7

Table 3 also shows the frequency of pop-ups of the norm-based support and the use of the support functions in the software. The former suggests that many mistakes are made during the construction of the model. To investigate this further, Table 4 shows how often students created, modified or deleted an ingredient and how many unique mistakes they made during the construction process.

Table 4. Summary of the number of create, modify and deleted actions, and unique mistakes.

Test	M	SD
Create ingredient	56	9.7
Modify ingredient	59	29
Delete ingredient	21	8.6
Unique mistakes	51	17

6.2.2 Pre- and post-test

Tabel 5 shows the results of the pre- and post-test. A notable finding regarding the open question is that, in both the pre-test and post-test, students mainly restricted their answers to identifying quantities that influence how the black hole is observed, while causal relationships between these quantities were only rarely mentioned.

On average, students mentioned 1.8 correct properties influencing the observation of the black hole in the pre-test, compared to 4.2 in the post-test. In the pre-test, students primarily referred to already known properties such as mass, radius, and distance to Earth. Several responses also included incorrect answers or minor details, such as 'objects moving in front of the telescope' or 'the speed of light'. Incorrect answers were not included in the scoring of this pilot study. The post-test responses did not contain misconceptions nor minor irrelevant details.

Table 5. Mean scores pre- and post-test.

Type	Mean pre (SD)	Mean post (SD)
System thinking	3.7 (1.2)	4.6 (1.4)
Domain knowledge	6.2 (1.3)	6.9 (1.2)
Open question	1.8 (1.4)	4.2 (2.4)

The results of the open question are shown in Fig. 10. Students were able to mention more factors influencing the creation of the image after completing the lesson activity, in particular properties of the black hole, accretion disc and telescope. In the pre-test, none of the students mentioned the accretion disc or the associated quantities. The increase observed in the category properties of the telescope was entirely attributable to students who had (almost) fully completed the model. None of the students who only completed the first two sections of the model mentioned telescope (related) properties in the post-test.

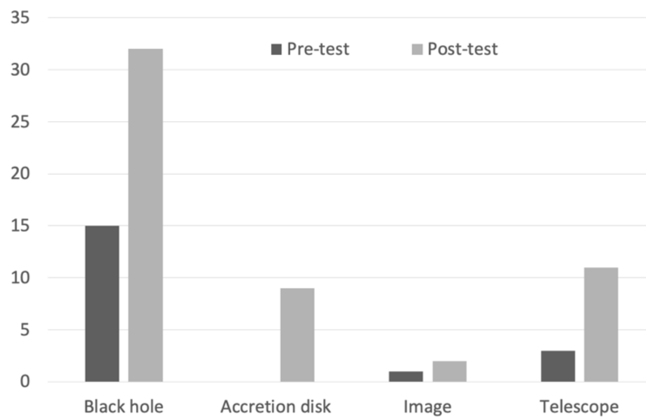

Fig. 10. Total number of correctly mentioned properties per category that influence how the black hole is observed in an image.

7 Conclusion and Discussion

This paper describes a lesson and a pilot evaluation in which students construct a qualitative model representing the mechanisms underlying the creation of an image of a black hole. The lesson focuses on identifying causal relationships between the properties of a black hole, its accretion disc, the telescope, and the resulting image. Rather than focusing solely on factual knowledge, the lesson aims to support students in reasoning about the mechanisms underlying black hole imaging. Pre- and post-tests were developed to evaluate students' progress in system thinking and domain knowledge.

Black holes are inherently difficult to teach about because many of the relevant phenomena cannot be directly observed. Understanding how images of black holes are produced requires students to reason about invisible mechanisms and the relationships between multiple interacting quantities. The lesson demonstrates how qualitative modelling can support students in making these otherwise abstract astrophysical observation processes more accessible.

The results show that students can construct the intended model when supported by the scaffolds provided in the software. However, the model is relatively large and the subject matter complex, resulting in not all students being able to complete the model within the allotted time of 80 minutes. Previous qualitative modelling lessons indicate that models of comparable size typically require more time to complete [14,16]. Nevertheless, all students in the present study reached the final section of the lesson, suggesting that the model size is appropriate and that extending the lesson to approximately 100 minutes would allow most students to complete the entire model.

Constructing the model proved challenging because students frequently made errors and often used the automated support functions to correct these errors. This pattern is consistent with previous studies [6–8,14,16]. It appears that students show statistically significant improvements in both content knowledge and systems thinking skills, regardless of their individual support usage patterns [16]. In the current pilot study, the results of the pre- and post-test also indicate improvements in both systems thinking and domain knowledge. Given the small sample size (N = 13), additional inferential statistical analyses add little value; we therefore interpret the results primarily as descriptive indicators. From this perspective, the findings are particularly informative for the design of the subsequent effect study: they provide insight into the suitability of the lesson design, the usability of the modelling environment, and the suitability of the assessment instruments. Within this exploratory framework, the observed improvements suggest that qualitative modelling supports the integration of domain-specific knowledge with systems thinking skills.

The results of the open question show that students mentioned a larger number of properties influencing how a black hole is observed after completing the lesson. In addition, no misconceptions or minor irrelevant details were found in the post-test responses. However, the open question appeared to place a relatively high cognitive demand on students, as it required them to simultaneously retrieve relevant quantities, reconstruct causal relationships, and verbalize these relationships in coherent prose. Most responses therefore consisted primarily of isolated quantities rather than explicit causal relations between quantities. The distinction between identifying quantities and reasoning about causal relationships is relevant from a system thinking perspective. Identifying isolated quantities appears to be cognitively less demanding than reasoning about the interactions between these quantities. The limited number of explicitly mentioned causal relations suggests that constructing a model does not automatically result in students verbalising system-level reasoning.

Interpretation of the improvement on the open question should also be treated with caution. It appears that during the post-test, some students may still have had the model open on their computer screens, making it impossible to determine to what extent they consulted the representation while answering the questions.

Future research could include a larger evaluation study, and while doing so grant students more time to complete the lesson. The open questions could also be reformulated to place greater emphasis on identifying properties that influence how the black hole is represented in an image. Additionally, students could be shown their pre-test responses during the post-test and be asked to revise or extend these answers. This approach would make it possible to investigate whether students actively correct earlier misconceptions rather than simply omitting them due to the large amount of newly acquired information.

It would also be useful to investigate how systems thinking and domain knowledge improve with repeated execution of lessons at a more complex modelling level and across various topics within astrophysics.

In our ongoing research, additional lessons are being developed focusing on other phenomena related to black holes. These lessons use the same or a higher level of model representation (levels 3 and 4), requiring more complex systems thinking. Current topics include phenomena that strongly appeal to students' imagination, such as escape velocity around stars and black holes, and the life cycle of stars.

Qualitative modelling appears to provide a promising approach for supporting secondary school students in reasoning about complex astrophysical systems that are otherwise difficult to observe and understand.

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8 References

[1] Jacobson, M., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *The Journal of the Learning Sciences*, 15(1), 11-34.

[2] Bredeweg, B. & Forbus. K.D (2016). Qualitative Representations for Education. In: R. A. Sottilare, A. C. Graesser, X. Hu, A. M. Olney, B. D. Nye, & A. M. Sinatra (Eds.), *Design Recommendations for Intelligent Tutoring Systems: Domain Modeling*, 4, 55-68.

[3] Forbus, K.D. (2018). Qualitative representations. How people reason and learn about the continuous world. Cambridge, Massachusetts: The MIT Press.

[4] VanLehn, K. (2013). Model construction as a learning activity: A design space and review. *Interactive Learning Environments*, 21(4), 371-413.

[5] Bredeweg, B., Kragten, M., Holt, J., Kruit, P., van Eijck, T., Pijls, M., Bouwer, A., Sprinkhuizen, M., Jaspar, E., & de Boer, M. (2023). Learning with Interactive Knowledge Representations. *Applied Sciences*, 13(9), Article 5256.

[6] Spitz, L., Kragten, M., & Bredeweg, B. (2021). Learning Domain Knowledge and Systems Thinking using Qualitative Representations in Secondary Education (grade 8-9). 34th International Workshop on Qualitative Reasoning, Montreal, Canada.

[7] Kragten, M., Spitz, L., & Bredeweg, B. (2021). Learning Domain Knowledge and Systems Thinking using Qualitative Representations in Secondary Education (grade 9-10). 34th International Workshop on Qualitative Reasoning, Montreal, Canada.

[8] Kragten, M., Jaspar, E. J. O. A., & Bredeweg, B. (2022). Learning Domain Knowledge and Systems Thinking using Qualitative Representations in Secondary Education (grade 10-12). 35th International Workshop on Qualitative Reasoning, Vienna, Austria.

[9] Sjøberg, S., & Schreiner, C. (2010). *The ROSE project - An overview and key findings*. In C. Schreiner & S. Sjøberg, *The Relevance of Science Education (ROSE)*.

[10] Salimpour, S., Bartlett, S., Fitzgerald, M.T. et al. (2021) The Gateway Science: a Review of Astronomy in the OECD School Curricula, Including China and South Africa. *Research in Science Education*, 51, 975-996.

[11] The Event Horizon Telescope (EHT) Collaboration (2019). First M87 Event Horizon Telescope Results. I: The Shadow of the Supermassive Black Hole. *Astrophysical Journal Letters*, 875(1), L1.

[12] The Event Horizon Telescope (EHT) Collaboration (2022). First Sagittarius A* Event Horizon Telescope Results. I: The Shadow of the Supermassive Black Hole in the Center of the Milky Way. *Astrophysical Journal Letters*, 930(2), L12.

[13] Abbott, B.P., Abbott, R., Abbott, T.D. et al. (2016). Observation of Gravitational Waves from a Binary Black Hole Merger. *Physical review letters*, 116(6), 061102.

[14] Fawzi, N., Kragten, M., & Bredeweg, B. (2024). Qualitative Reference Model for Learning about Melatonin Regulation. 37th International Workshop on Qualitative Reasoning, Santiago de Compostella, Spain.

[15] Bredeweg, B., Liem, L., Beek, W., Salles, P. & Linnebank, F. (2010). Learning spaces as representational scaffolds for learning conceptual knowledge of system behaviour. In: M. Wolpers, P. A. Kirschner, M. Scheffel, S. Lindstaedt, & V. Dimitrova (Eds.), *Technology Enhanced Learning*, LNCS 6383, 46-61. Springer, Cham.

[16] Kragten, M., & Bredeweg, B. (2024). Calcium Regulation Assignment: Alternative Styles in Successfully Learning About Biological Mechanisms. In: A. M. Olney, I.-A. Chounta, Z. Liu, O. C. Santos, & I. I. Bittencourt (Eds.), *Artificial Intelligence in Education*, LNCS 14829, 220–234. Springer, Cham.