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Storytelling as a Skeleton to Design a Learning Unit: A Model for Teaching and Learning Optics

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Abstract: Instructional design is an essential part of teaching practice: both researchers and teachers are engaged in finding strategies to deal with this complex work. We propose the use of storytelling as a skeleton to structure a long-lasting teaching unit, maintaining coherence and giving meaning to its various elements. We refer to an interpretation of storytelling for educational purposes as a role-playing game, drawing inspiration from the Digital Interactive Storytelling in Mathematics framework. Designing a learning unit based on storytelling means integrating every moment of the teaching–learning process within the narrative: the teacher and students are all part of the same story, which motivates every activity carried out in the unit and contextualizes the tasks performed. Moreover, the assessment is also integrated into the narrative flow. In this study, we designed an exemplary Storytelling Learning Unit (SLU) model for the study of light, promoting modelling and argumentation skills in mathematics and physics. This unit, intended for ninth-grade students in an Italian scientific high school, was co-designed by the teacher of the class in which it will be implemented. This work particularly focuses on the design process. From reflection on the specific unit developed, general design principles for creating a SLU were hypothesized.

Keywords: argumentation; design principles; instructional design; mathematics education; modelling; physics education; storytelling in education; teaching–learning optics

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1. Introduction

The practice of instructional design (ID) is defined as a systematic process to create an educational pathway, with the aim of enhancing efficiency and attractiveness [1]. This encompasses, on the one hand, determining teaching objectives by analysing learners' needs (i.e., learner analysis, task analysis, and needs analysis) and, on the other hand, developing a suitable structure that fits the objectives with these needs and assesses learning outcomes (i.e., assessing learner achievement and evaluating the success of the instructional design) [2].

ID provides educators with a structured framework to develop targeted and effective educational pathways, fostering reflection on teaching and learning, adapting to the needs of students, and delivering high-quality education. Indeed, the advantages of ID are multiple: starting to think about details, defining what to teach and planning how to carry it out, anticipating and resolving potential difficulties that students could encounter, and reflecting on actions to reshape processes and routines [3]. Furthermore, making use of ID seems to be particularly useful in attaining higher achievement rates in mathematics [4].

However, as emphasized by Visnovska and colleagues [5], ID is by no means an easy challenge for teachers. The complexity that lies behind this practice is often underestimated when considering the gap between the intended curriculum and the enacted curriculum. Pre-service and in-service teachers need concrete examples to constructively put teaching designs into practice [6–8]. The examples help the teacher to transfer and adapt the models to make them useful in new situations, to see the practical consequences of using the instructional models, and to make considerations later for their contexts [9,10].

We identified storytelling as a possible tool for guiding ID. The advantages of incorporating storytelling into the educational context, both as a teaching tool for instruction and as a learning resource for students, have been widely studied in the literature of the field [11–16]. Indeed, throughout history, storytelling has been a valid method that humans have used to share and convey knowledge. The metaphor of storytelling is used as a methodological context in which the teaching–learning process unfolds. In education, it can make the learning environment more enjoyable and knowledge more accessible, engaging students at the non-cognitive levels of emotions and imagination.

For mathematics, physics, and, generally, sciences education, the narrative form is a valid tool for humanizing the teaching and learning of science by creating anticipation, stimulating students' curiosity, and promoting a sense of wonder in the presentation of scientific processes and results. Furthermore, it can also promote deeper and more lasting understanding, motivating and facilitating learning. Indeed, a story does not just present concepts but connects actions and intentions, desires, beliefs, and feelings in a situated context, allowing the construction of meanings [17]. This perspective is especially consistent with the concept of appropriation [18], which requires culturally (and not only scientifically) relevant teaching materials, and activities, like open discussions on different perspectives or epistemological viewpoints, that allow viewing physics, mathematics, and other sciences as a continuous process of widening and refining knowledge. This contributes to reshaping the authoritative image of science. For this reason, an opportunity for students to express themselves regarding the content being presented is a fundamental requirement.

It seems particularly promising to integrate storytelling activities in which students take part as main characters in the story, from the perspective of role-playing games. Moreover, in the context of education, some further measures are necessary to make the narrative being told meaningful for students. The issue under discussion must be open to challenges, so that it is possible to imagine that the characters can influence the course of the story, which depends, in some way, on the response to the questions posed [19].

Therefore, the perspective of storytelling we have embraced aligns with that found in the DIST-M (Digital Interactive Storytelling in Mathematics) framework [16]. Within this framework, students are asked to deal with problems placed in narrative form. The story evolves over time, and each student plays a different role within each scene of the plot. As part of their roles, each student performs three consecutive actions—Inquiry, Conjecture, and Proof—actively participating in the story's progression. The Inquiry expects each student to form and share their own conjecture about the given mathematics problem with their classmates. The Conjecture focuses on improving the social aspects of the content and formal expression that students produce on their own. In this phase, students begin with what they have found and shared and engage in a discussion with their peers to produce a shared conjecture that they can then communicate to an expert. Finally, the Proof is the stage when the shared conjecture that emerged from teamwork is organized into a formal mathematical proof [20]. However, unlike this model, we do not intend to develop the design within a digital environment.

In our proposal, we focus on an interdisciplinary didactic unit exploring light, concerning modelling and argumentation as key competencies to be developed in mathematics and physics.

Modelling is a central activity in all sciences [21,22]. If one of our purposes is that students learn physics by thinking like physicists, by engaging in activities that mimic the actual practices of physics, and by using the reasoning tools that physicists use when constructing and applying knowledge, as theorized by the ISLE approach [23], working on models could be very productive. In recent decades, an explicit discussion of modelling has acquired a significant role, e.g., the 2012 Framework for K-12 Science Education [24] articulates "Developing and Using Models" as one of the key science and engineering practices that should be emphasized throughout the K-12 curriculum. The Framework for K-12 Science Education outlines the role of modelling within the broader context of scientific practices used by scientists and engineers. One example of a teaching approach that integrates modelling with experiments is the Investigative Science Learning Environment (ISLE) curriculum. This curriculum follows a learning cycle that involves making observations, identifying patterns, creating explanations, articulating assumptions, making predictions, testing predictions, and then revising models and experiments. In the Italian scenario, we can integrate modelling following the National Indications [25]. In this document, we find the competencies that students are supposed to have acquired at the end of scientific-oriented high school, and particular models are explicitly mentioned: "*formulating explanatory hypotheses using models, analogies and laws; [...] constructing and/or validating models*".

Indeed, on the one hand, argumentation serves as a fundamental medium for activating learning processes [26], and, on the other hand, discussions in which students can speak freely about the content they face lead to appropriation [18]. As emphasized in the studies carried out by Albano et al. [27], storytelling is a promising strategy for working on argumentative competencies.

To develop these competencies, we chose a core topic in science: the study of light. It is a theme strictly connected to the comprehension of models, it evolves over time, and it is integrated into the Italian National Indications [25]. Indeed, in the first two years, the National Indications provided for the treatment of geometrical optics, with particular attention paid to the phenomena of reflection and refraction of light and the functioning of the main optical instruments. Students are introduced to the modelling of real situations. The study of light continues in the second two years, through wave optics, and in the fifth year with the characterisation of the electromagnetic nature of light. Finally, in the final year, the photoelectric effect is treated as a crucial experiment to address the theme of wave–corpuscle dualism, leading to the introduction of the quantum object.

With the presented contribution, we provide an exemplary design of a didactic unit framed upon narration. Therefore, we will present, as a model, the script of the didactic unit integrated into the curriculum and developed as storytelling, accompanied by some examples of didactic materials designed for its implementation. Additionally, we will try to hypothesize key principles for the design of a Storytelling Learning Unit, hereafter abbreviated as SLU, starting from this case study we are working on.

As a first step in the research, the aim of this paper is elucidating the process involved in designing the SLU, providing in-depth insights into the theoretical and didactical assumptions that underpin our approach, and presenting a set of design principles, albeit as a hypothesis, which can guide the creation of the SLU. At this stage, we have not undertaken the validation of these hypothesized design principles. Instead, we defer the validation process to subsequent research endeavours. These future research initiatives will commence with an analysis of data derived from the actual implementation of the SLU in a classroom setting. This data-driven approach will allow us to investigate the effectiveness of the SLU's implementation and of the design principles we propose.

2. Research Design and Methodology

In selecting a particular context and core content from the curriculum suitable for experimental activities, we endeavoured to incorporate storytelling principles into the design of a learning unit, employing specific techniques such as backward design [28] and inquiry-based learning [29]. The resultant learning unit, integrated into the curriculum, aims to develop modelling skills and argumentative skills, giving relevance to formative assessment strategies [30,31].

In the following paragraphs, we will present the context, objectives, and the structure of the designed learning unit and the scientific problem.

2.1. The Context

The intervention has been designed for a first class (14/15-year-old students, grade 9) of a Liceo Matematico [32], which is a scientific high-school curriculum with two extra hours per week for mathematics and physics boosting. One of the strengths of the design is the possibility of the physics course class teacher being involved in the research group, so that the unit can be co-designed by the researchers and the teacher-researcher.

We consider it is crucial to put the work into actual reality to make it effective. Consequently, several decisions were dictated by the specific context. For instance, the selection of a story contextualization, inspired by *The Lord of the Rings*, stems from a genuine interest observed among the pupils in the class. Furthermore, other design features and objectives for the learning unit align with the specific characteristics of the classroom. It is composed of 18 students, including a student with learning difficulties (dyslexia). Students show curiosity and interest and appreciate the laboratory activities, so the planned activities are suitable for the class. Some group dynamics need to be kept under control, but in general, the climate is positive. Although the environment is conducive to dialogue, only a few students habitually intervene in whole-class discussion. This may be due to personality traits, habits acquired over time, or new social dynamics being created that sometimes place the student in an observational attitude. This context has been chosen for precisely these characteristics, so storytelling can help overcome the fear of intervention, and the role-playing game can make one feel less judged by others and encourage involvement. Moreover, this intervention aims to provide useful feedback to students to support their learning and their behaviour.

The time schedule of the physics course is two hours per week, but thanks to the boosting experimentation we can have two more hours per week to use.

2.2. The Didactic Unit: Teaching and Learning Optics

The exemplary unit is specifically developed to be focused on modelling, linking physics and mathematics. In particular, this case study focuses on the teaching and learning of optics. This intervention is conceived such that students will achieve the following:

- Enhanced argumentation and modelling skills in physics and mathematics.
- Address one of the pivotal themes of physics, light, more completely and profoundly.
- Promote a view of science as a social and living process.
- Promote self-assessment on several levels that are linked to disciplinary content, related to the collaborative dimension, as well as argumentative competence.
- Be encouraged to participate and then overcome their fear of taking action as, through storytelling and role play, they will be able to feel less judged by others and more involved.

2.2.1. Design Choices

A backward design [28] approach has been adopted in order to identify and make explicit the enduring understandings that the students should acquire. This approach also helps with planning appropriate activities to achieve established goals, also paying attention to the progress of the physics curriculum in the following years. In this way, we encourage enduring understanding and make the content relevant and meaningful within the framework of students' development. The enduring understandings are associated with some essential questions that are open-ended, thought-provoking, and intellectually engaging, promoting discussion and debate; they call for higher-order thinking, such as analysis, inference, evaluation, and prediction; essential questions point toward important, transferable ideas within disciplines; they raise additional questions and spark further inquiry; they require support and justification, not just an answer; they recur over time, and they can and should be revisited again and again.

The essential questions chosen for this unit are: "how does light interact with matter?" and "what models can we use to explain light phenomena and what is their validity?"

Moreover, in backward design, after outlining the goals, we plan out assessments. The destination is chosen first to be clear about what we want the students to know and be able to perform. Our final problem consists of designing tools (practical) and explaining light (theoretical). However, although we thought of the final task as a summative assessment, we envisaged a set of intermediate activities that are valid as a formative assessment.

The activities are outlined according to an inquiry-based learning paradigm, in particular, the ISLE (Investigative Science Learning Environment) model, which has inspired the use of different kinds of experiments (observational, testing, application), the structure of the laboratory worksheets, and the assessment rubrics, as in Etkina et al. [33–35].

2.2.2. The Scientific Problem

The unit means to address a scientific problem through a narrative struggle. The scientific issue is summarised in a concept map in Figure 1, and it concerns the nature and propagation of light, in particular the three models to represent light (ray, wave, and particle models), how light travels (the linear propagation of light), and when light interacts with matter (the phenomena of reflection and refraction).

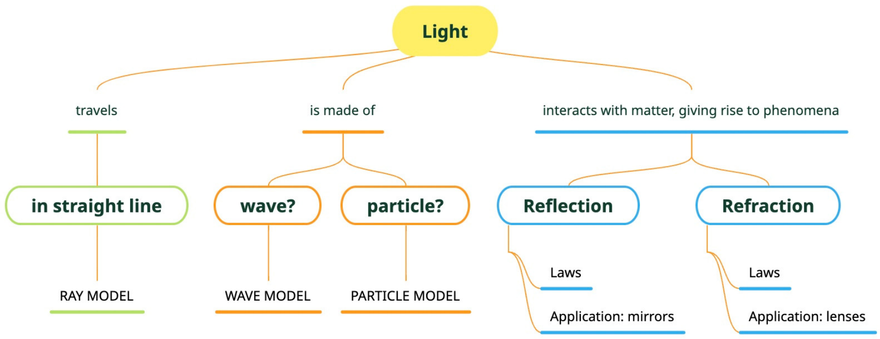

Figure 1. Concept map of the unit.

3. Results

The resulting SLU will be presented in this section, illustrating the structure and details of the script and showcasing some exemplary materials tailored for classroom implementation.

3.1. Identikit of the Unit

In the following lines, we briefly summarise the contents (Figure 2) and the desirable learning outcomes (Table 1) of the resulting unit.

Contents

Physics	Models of light (ray/particles/waves models) and explanation of light phenomena through different models of light
	Light propagation
	Reflection and refraction of light
	Mirrors and lenses - application of reflection and refraction
Mathematics	Geometrical properties of angles and triangles
	Equations
	Sine as an input-output machine (as an example of a generic function: the idea of a function as an input-output machine)
	Geometrical introduction of the tangent line/curvature
Meta - contents	The role of models: their relationship with observation in science and for the scientific investigations
	Sciences investigation is a social activity (i.e. the scientific community and its discoveries grow through dialogue, confront, travels, people) and a living, ongoing process that proceeds to intertwine theoretical and technological developments
	The link between mathematics and physics, overcoming the barrier between the two disciplines

Figure 2. Contents of the SLU.

Table 1. Learning outcomes of the SLU.

Students' Achievement of Content Objectives and Meta-Objectives	
LO1	Can explain the ray model of light (understanding)
LO2	Know and compare models of light, identifying the range of validity, strengths, and weaknesses (understanding and analysis)
LO3	Can explain certain phenomena concerning light–matter interaction, can predict the results of an experiment and mental experiments on light–matter interaction, and can solve problems (understanding and application)
LO4	Can use mathematics to identify, compare, and generalise and formulate laws (geometry, sine function, and basic algebra) to solve problems in optics (application, analysis, synthesis)
LO5	Can use the laws of refraction to recognize and calculate the properties of substances (application)
Growth in expository and communication skills	
LO6	Can argue to construct explanations from observations and reflection on experimental evidence, from solutions to a specific problem, and can compare different models on the basis of acquired knowledge (evaluation)
Peer collaboration	
LO7	Can listen to the opinions of peers, explain and support peers, collaborate in order to converge on one or more shared solutions, and can compare notes
Active participation and responsibility for own learning	
LO8	Actively participates in discussions: responsible for solving problems and responsible for expressing their own thinking

The learning outcomes of the designed SLU are formulated according to Bloom's taxonomy, specifying the category of belonging (in brackets).

3.2. The Structure of the Unit

In our study, storytelling is a model for projecting a didactic unit developed into cycles articulated into the following stages:

1. Exploratory stage.
2. Conflict/generation/conjecture phase.
3. Formalisation–demonstration.
4. Modelling/application/transfer to other contexts.
5. Assessment.

Each cycle is part of the storytelling and includes opportunities for self-assessment and personal feedback from the teacher and researcher.

The SLU is articulated in three main cycles, and each one covers a DIST-M cycle. Each cycle starts with Inquiry and Conjecture activities (points 1 and 2 of the aforementioned list) and then proceeds with tasks and discussion concerning Arguing and Proof (point 3), ending with a Summing up and Refining section (points 4 and 5).

The phases are not sequentially organized: a macro-cycle, concerning models of light and the key questions illustrated in Figure 3, starts in the introductory part and continues in the conclusion of the unit. Between these two sections, the other two DIST-M cycles, thematically characterised, take place: the reflection cycle and the refraction cycle (Figure 3).

3.3. The Narrative Structure

Through the narration, students start a journey to gain the experience needed to face some adventures and to achieve the abilities necessary to reach the final goal of our story. They are part of the story, as well as the teacher, living the experience first-hand.

The whole storyline of the resulting SLU is detailed in Appendix A. In this section, we offer a few examples to provide insights into how the narrative has been seamlessly integrated with the disciplinary learning objectives.

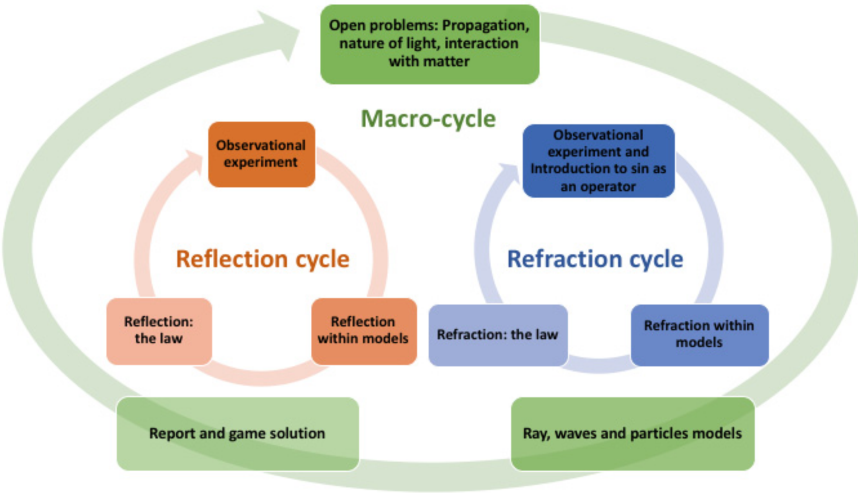

Figure 3. The cycles of the unit.

In the following, we present an example of integrating narrative with experimental activities to reach an understanding of the ray model. The worksheet, reproduced here in its entirety, also contains self-assessment questions.

The following narrative script is told by the teacher with the help of images to create a suitable atmosphere:

> "*After walking all night trying to reach the company, suddenly our heroes are surrounded by hordes of orcs and the only way to escape is a door in the mountain.*
>
> *Fortunately, the sun is rising, a ray hits the gates, and they open!*
>
> *This happens only on very particular moments. Destiny? Luck? Or perhaps the powers of light... Galadriel was right.*
>
> *Our characters are saved from the orcs! But the dwarves, who are used to the darkness of these places, notice another danger. There are rays to defend the entrance, if they interrupt the beam a trap is triggered. What can they do to enter unharmed?*"

The teacher takes the dwarves aside and shows this group of students only what they see, so that they can further explain it to their classmates. Then, everyone tries the experimental part together with other characters but responds individually to the worksheet, illustrated below (Figure 4).

At the end of each stage, after completing a worksheet, students are asked to answer some questions to reflect on the activity, on their behaviour during the activity, and on the group work (if it is a collaborative work). The meaning is to induce a self-evaluation to become more aware of themselves. We plan to collect all the worksheets and self-evalutation forms, in order to give feedback to students on their learning progression, and thus sustain a formative assessment. Moreover, the progression of the learning journey is highlighted by introducing an experience point system.

Below, the self-evaluation questions, given to students after the introductory task, are illustrated.

Let's take stock... It's time for self-assessment.

1. *What are the 'big ideas of physics' which are the focus of this lesson?*
2. *How do they relate to what I observed in reality or what I already knew?*
3. *Were there times when I found it difficult? What happened when/if I got stuck or did not understand?*
4. *Did I actively participate in the lesson? Was I able to explain and present my ideas?*
5. *Were the tools, explanations and material used helpful for me to understand? What in particular? What not?*

6. *Did the lesson help me to understand how to think as a physicist/mathematician to approach a phenomenon?*
7. *Did the lesson help me to think more deeply about the issues addressed?*
8. *Is there anything you would like to ask a classmate to explain to you that you are not sure you understand?*

Quest n.1 - Introductory task

Objectives

• to understand

i. how light travels
ii. what is needed for us to see
iii. if light interacts with matter

General material

lamp, candle, laser, torch, sun with obstacle (shadows), mirrors and transparent materials.

Observational experiment (by Etkina)

Equipment: an absolutely dark room, a laser pointer, and a spray water bottle.

a. Go into a room that is completely isolated from all external light sources—natural and artificial. Turn off the internal lights and wait in the dark room for several minutes.
Record your observations and propose an explanation.

b. Take a laser pointer and point it at a wall. Can you see the beam of light it sends or only the shiny spot on the wall? What path did the light follow to reach the wall? You can find it by trial and error - by trying to block the light with a small piece of paper at several locations along its path to the wall, or by using the water spray bottle.

c. What can you say about the path of the light from the laser to the wall? Represent that light path by a long line with an arrow, called a ray. A ray is not real; it is just a way to show the direction that light is travelling.

d. Explain why the water droplets (or chalk dust) make it possible to see the light beam that was previously not visible.

e. Discuss the conditions needed for us to see something.

f. Use the laser and the torch with different materials (mirrors, transparent objects) and describe what you observe.

Conclusion

How does light travel? [+4 XP]

And what can you say if the source is far away (the sun)? [+2 XP]

What do we need to see? [+2 XP]

Does light interact with matter? And if so, in what ways? [+2 XP]

Figure 4. Example of worksheet for students.

The final report and the solution of the conclusive problems are part of the summative assessment. In each stage of the SLU implementation, providing students with as much feedback as possible, assessing the different skills further than the knowledge involved, is considered essential to scaffold them and support their learning process. In addition, the learning outcomes are shared with students to make explicit the importance of their growth in skills, peer collaboration, active participation, and responsibility for their own learning. These dimensions are effectively part of the final grade.

4. Discussion

A possible interpretation of the storytelling for the design of a didactic unit and the exemplary model, briefly presented in the previous section, is intended for the specific selected context. We addressed a particular topic, the study of light, in response to certain contextual needs, promoting argumentation and focusing on a meta-reflection on the nature of science. However, we believe that, in response to similar objectives (in terms of content and teaching needs), the unit can be modified in relation to other contexts and needs. For instance, the focus can always be on modelling but referring to different school grades (e.g., focusing on more advanced contents), or it can be readjusted for different typologies of high schools. In designing the resulting SLU, we have identified some conditions for structuring a SLU that can be transposed to other contexts, further than recognizing some particular features inherent to the specificity of our proposal. It is, therefore, appropriate to outline what we consider to be the characterising aspects of SLU design, and thus generalisable to other contexts, and which aspects are specific to our exemplary case. From an a priori analysis, we hypothesized seven key principles of general concern for designing a SLU, illustrated in the following table (Table 2).

Table 2. Design principles of a SLU.

Design Principles of a Storytelling Learning Unit	
1	Write a story that allows for a common thread, keeping in mind a backward design approach, with a focus on the learning outcomes and the assessment criteria.
2	The narrative must justify the tasks assigned to the students, and the chosen problems the students deal with have to be open to different solutions.
3	The unit framed upon the storytelling has to follow one or more narrative cycles (e.g., according to the stages of the DIST-M model).
4	The teacher and students have to all be part of the same story. Creating one's own character within the story (role-playing game) allows for greater involvement and lowers levels of peer judgment.
5	Integrate into the story experiential activities in which students can enact what is expected to be learned.
6	Self-assessment and teacher evaluation of the students' learning process and learning outcomes, conceived as a formative practice, have to be an essential component of the narration itself.
7	Provide worksheets that help students to individually express themselves in writing, reflecting also on their own learning process and creating moments of whole-class discussion to encourage oral exposition and co-construction of knowledge with peers and the teacher.

From the specificity of the exemplary unit presented, some other recommendations for the design of a SLU are necessary:

- *Topic covered.* Light is a relevant topic, suitable to be explored in depth by dedicating time and effort. Indeed, we think that, generally, the scientific theme of a SLU should be among the core topics of the curriculum; thus, this type of planning, which demands a great amount of time and energy spent on design and implementation, can offer an opportunity to reflect on fundamental topics of the subjects involved.
- *Story.* The narrative must encounter students' and teachers' interests. The specificity, from the context and content selected, allows us to reflect on the importance of the narrative frame chosen for the unit. *The Lord of the Rings* is the particular frame chosen for our case because the teacher knows that it can be of interest to the students in this classroom. Considering the same topic, but implementing it with other students, another background could be a better choice. Therefore, knowing students is important as well as involving the teacher of the class in the design of the SLU.

- *Competencies*. The competencies we aim to boost by carrying out the unit are modelling and argumentation: we believe that they are particularly suited to be developed with a SLU. However, depending on the learning outcomes selected, other skills could be strengthened by this type of unit, but this requires further investigation.
- *Meta-outcomes.* If the SLU is considered as a way to promote the awareness of the nature of science, e.g., as in our case with modelling as an argument to be developed between mathematics and physics, take care of the aspects characterising the involved disciplines: e.g., in our design, consider the experimental part for physics and the deduction of laws for mathematics.

5. Conclusions

What we call a Storytelling Learning Unit (SLU) is an innovative way of designing a learning sequence that has the advantage of contributing to long-term planning while maintaining an organicity often perceived as lacking in school settings.

Indeed, storytelling offers the possibility to smoothly articulate the various stages of a learning path, emphasizing the essential questions that characterise the proposal and giving students time to go deep into the covered topics.

Furthermore, in our project, we interpreted storytelling as a role-playing game, which is a key element for student engagement: through the narrative, the student is involved in the development of the unit, aware of the learning path, and responsible for it. A significant role in taking care of these elements is played by formative assessment strategies. Implementing an assessment process integrated into the story seems to enhance both the narrative as a learning device and the objectives of assessment (from the perspective of formative assessment) itself.

Students are faced with challenges and problem-solving arguments that they are called to struggle with. If specific worksheets are designed to give students the opportunity to explain, by writing, what they have experienced and learnt, and whole-class discussions are integrated to promote the co-construction of knowledge, it can be a precious occasion to foster argumentative skills.

Finally, first-person involvement allows students to experience scientific practice, enabling significant reflections on the nature of science. In summary, storytelling allows subjects to be combined fluidly, developing a learning path organically between historical aspects and the nature of science and enabling students to address relevant questions and be part of their learning process.

In this paper, we have presented an example of a didactic unit which can serve as a framework for designing learning paths integrated into the curriculum and articulated in storytelling.

It can be adapted to different situations, both in terms of the unit's content and the classroom context (grades, classroom characterisation, etc.). However, not all of them may be suitable for developing a SLU: since the structure of the exemplary SLU illustrated, we believe having similar objectives is a relevant condition for its application. Furthermore, we believe this effort can be worthwhile for focusing on a key topic of the curriculum, since it requires a demanding amount of time to be covered and effort to be designed and implemented.

This research has provided a detailed explanation of the instructional design process for the SLU example. Nonetheless, further research efforts are necessary to assess the educational effectiveness of the SLU concerning its stated objectives. Furthermore, it is crucial to validate the hypothesized design principles by analysing them toward the outcomes observed during the actual classroom implementation of the SLU and considering subsequent design refinements.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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Appendix A

The beginning of our story starts with the following paragraph from *The Fellowship of the Ring*, chapter Farewell to Lórien, by Tolkien:

> "*And you, Ring-bearer,' she said, turning to Frodo. 'I come to you last who are not last in my thoughts. For you, I have prepared this.' She held up a small crystal phial: it glittered as she moved it, and rays of white light sprang from her hand. 'In this phial,' she said, 'is caught the light of Eärendil's star, set amid the waters of my fountain. It will shine still brighter when the night is about you. May it be a light to you in dark places, when all other lights go out.*"
>
> *Frodo, Sam, Merry, Pippin, Aragorn, Boromir, Gimli, and Legolas leave.*
>
> *A new group of characters arrive at Lórien, and Galadriel now speaks to them: 'The Fellowship's members need all the help they can get. The light is important to win against the Dark forces of Sauron.*
>
> *To gain the needed experience to face the challenge, you have some quests to complete. When you will be ready, you can join the Fellowship against the Dark forces of Sauron. So reach them!'*
>
> ***But... what is light? And how can we help the Fellowship against the dark forces of Sauron?***

Here, students are asked to create their character. We construct a sheet to help them with the character design. Paying attention to the design of characters can enhance the overall experience of a role-playing game.

We have selected some races from Tolkien's world and associated them with special abilities useful for our adventure: the human being has access to additional documents about history and can read the language of humans in libraries; the elf has the wisdom of words (a bonus in discussions and oral communication); the hobbit has excellent writing skills (a bonus in written communication); the dwarf has manual skills (a bonus in experiments) and sees well in the dark. Bonuses can be implemented in the form of cards, tips, and access to additional documents. If a character is missing in a group, for some reason, the others must do his/her part. During the activities, every worksheet will be collected to give students feedback to monitor the process of building knowledge. The experience point system is a way of making learning progression explicit to students. To stimulate a reflection on values owned by students, we ask them to write down the values (curiosity, patience, commitment, fairness, respect, etc.) they can share with others. Moreover, each student is included in a faction (wave or particle), which is useful for further group work. Then, to bring out their prior knowledge, we add to the worksheet some questions such as "What do you know about light? What is a model? Can you report some examples of models in physics?". Finally, we propose some questions about their consideration of mathematics and physics, their relationship with these subjects, their strengths and weaknesses, and their expectations of this unit.

After Galadriel speaks to them, they leave in search of the Fellowship. She turns around and invokes the souls of Newton and Huygens to follow the new company to help them (science will help, they do not have magic but they have science).

After walking all night trying to reach the company, suddenly our heroes are surrounded by hordes of orcs and the only way to escape is a door in the mountain.

Fortunately, the sun is rising, a ray hits the gates, and they open!

This happens only on very particular moments. Destiny? Luck? Or perhaps the powers of light... Galadriel was right.

Our characters are saved from the orcs! But the dwarves, who are used to the darkness of these places, notice another danger. There are rays to defend the entrance if they interrupt the beam a trap is triggered. What can they do to enter unharmed?

Now, an observational experiment will be proposed to students to promote the understanding of how light travels, what is needed for us to see, and if light interacts with matter. Here, the ray model is acquired.

Past the entrance, a fork in the road opens. One road leads downward and one upward. The spirits of Huygens and Newton then decide to intervene. Huygens approaches some of our heroes and suggests going downward; Newton suggests following the other road.

They divide. The group following Huygens finds a little lake down the road, and they see beyond it a door.

The other group, on the other hand, follows the road, which at one point stops and they see, beyond a small ravine, a door. The jump is not big but the important thing is to be able to open the door.

The light is again the key. But they don't have any source of light. They have to simulate it. . .but with particles (little balls) or with waves.

Newton and Huygens help the characters to better understand the situation.

Here, we want to try to answer the following questions: What is light made of? Is it made of waves or particles? This introduction to the models is made to understand if the ray model of propagation is coherent with the two models proposed through some hands-on activities.

Both groups manage to get out! And they find themselves in the same courtyard. They tell each other how they managed to cope, comparing their strategies.

However, they notice that the courtyard is all fenced off.

There is a kind of very small tunnel, it is too small to go through. But at the bottom of it, they seem to see a shimmer, maybe there is a mirror. It seems to be necessary to use light again to get out. . .

This is the moment when a new question arises: how does light interact with matter? Students experience the reflection phenomenon to devise a rule for specular reflection (observational experiment).

The spirit guides suggest controlling if the conjecture is valid also for the two models.

We continue to investigate reflection but with the models to check if the models are consistent with the rule for specular reflection.

The company understands the law and they are able to hit the spot using the mirror to get out.

The reflection law is formalised and the problem solved.

They arrive in a village and need to figure out where to sleep and eat. They hear that the innkeeper has a problem to solve and, having no money, they propose an exchange to the innkeeper: 'we will solve your problem in exchange for room and board'.

We apply the law of reflection to different situations to solve some problems and carry out testing and other observational experiments.

They eat breakfast and watch a spoon in the water, so one of them tells that when he/she washed, he/she saw his/her feet in the basin, they looked strange. Another character says that he/she dropped the soap in the water and to pick it up it was in a different place from where it seemed to him/her. . .

Now, the question is: how does light interact with transparent matter? Experiment with refraction in different situations to find a pattern in the path of light through different media.

Our heroes finally reach the Fellowship! But they had to protect themselves with a strange technique: the entrance of the gate seems frozen in a sort of substance similar to glass. . . They can see the stairs and a plate! It's a code. . . Only the worthy can enter.

After decoding the message, they understand that if they can hit the switch with the light, they will be able to enter. But they only get one try.

They go back and go to a glass artisan so they can do experiments in order to understand how the law of this phenomenon works.

Students look for regularities through experiments.

Not understanding the regularity, they go to the library and find writings in human language; only humans can read them.

They search for a new useful function: the sine function. Then, they study it and try to apply it to our data to derive a law. This phase is supported by the use of simulation and an applet (e.g., PhET Interactive Simulations by the University of Colorado).

It is important that the law is correct, they have only one attempt otherwise the mission will be failed.

They check with the models by talking to Huygens and Newton. . .

We continue to investigate refraction but with the models to check if the models are consistent with the rule for refraction.

. . .and it's fine.

They still check, trying to apply the law to see if it predicts well the behaviour of light when it passes through transparent materials. They have to be really sure before they exploit their attempt. And it works!

We formalise the law of refraction and apply it to different situations to solve some problems.

They then manage to reach the Fellowship.

'Tell us what you have understood (knowledge is essential for survival). But first, write it. Writing is personal. It represents us when we are absent in space and in time. Writing expresses who we are, even after our lifetime. It makes our knowledge, our personal aspirations and our work for the future visible to others. Writing is the means to explain our ideas to ourselves and to others while preserving our personal experiences and our memories. No one else can do it for you. In this way, writing connects you with yourself. Writing is not fleeting; it is permanent. It is a record of what you wished to communicate at a point in time.

Writing enables you to reach many places over time. Keep this in mind, it lives on in the minds of those who read it.

Words are powerful, they can be spelt and rich in magic. The universe was created through music and song. Gandalf warned us regarding Saruman, to not let him speak, implying there's power in the words that he speaks.'

Students summarise what they have learnt, writing a final report to answer this question: "So what does light do and what is it?"

'Now you have reached the knowledge and the experience to help us.

You can build an instrument that can be very helpful for the battle against the Dark Lord: a tool that allows us to see the enemy without making us see ourselves.

Moreover, to keep the orcs far away and weaken them, we can use light. The Orcs detest the sunlight and the reason is down to the time and place of their creation. Morgoth bred the Orcs at a time when Middle-earth was still shrouded in darkness, the light of the Two Trees of Valinor unable to reach the furthest corners of the world. As such, the Orcs were literally born in the dark, fighting and thriving in the black of night. When the sun rose over Middle-earth for the first time years after their initial creation, the light traumatised the Orcs, burning and blinding them after so many years shrouded in darkness. And their preference for darkness remains with them. We can exploit this weakness. What mirrors could we use to channel light into the orcs' hiding places?

Then there is another problem. Sometimes, when elves are hit with narrows, they can be poisoned. The substance injected goes into the blood and we should recognize its presence as soon as possible, to prevent the poisoning from spreading throughout the body. How can you determine the concentration of this substance, using light? This substance is similar to human sugar and to test your system you can use water instead of blood. We cannot waste a single drop of blood of our valiant fellows.

It is time to help and do our part: applying the knowledge acquired to new situations, they can solve new complex problems.

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