IMPRESSions of the Invisible: New Approaches in Modern Physics Education

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Abstract. This symposium, organised by the International Modern Physics & Research in Education Seminar Series (IMPRESS), addresses the intangible and abstract nature of modern physics concepts. Four contributions explore innovative approaches for conceptualising topics of relativity, quantum physics, and astrophysics across primary to tertiary education. Contributions include physical analogies for exoplanets, a simulation-based environment for special relativity, expert strategies for understanding spatiotemporal scales, and a spiral curriculum introducing modern physics to primary school students. These diverse approaches are united by their potential to make intangible phenomena comprehensible for students and embody IMPRESS's mission to enhance the impact of modern physics education.

Introduction and background

The field of modern physics has seen significant scientific progress in recent years, leading to its emergence as a key component of physics education worldwide. Incorporating topics of relativity, quantum physics, and astrophysics into school curricula generates both enthusiasm and instructional challenges. While these learning domains offer great potential to increase student interest and improve attitudes [1], their abstract, intangible, and often counterintuitive nature necessitates the development of innovative instructional approaches [2].

The formation of the International Modern Physics & Research in Education Seminar Series (IMPRESS) represents a concerted effort to share and disseminate such instructional approaches and, ultimately, enhance the impact of modern physics education research and practice [3]. IMPRESS, a joint initiative of the Physics Education Research groups at CERN and the University of Copenhagen, illustrates how the physics education community can **embrace changes together** in line with the theme of the 4th WCPE. By organising monthly seminars and providing a platform for collaboration and exchange[1], IMPRESS aims to build bridges between physicists, educators, and learners.

Problem statement and the role of each contribution

This symposium, organised under the IMPRESS initiative, addresses a key challenge in modern physics education: the intangibility of phenomena that elude direct sensory perception and often defy everyday experiences [4-6]. Recognising the need for instructional approaches that make these concepts accessible to learners from primary to tertiary education, each contribution addresses a specific instructional challenge and showcases a distinct approach aimed at conceptualising invisible and abstract concepts of modern physics.

Oriel Marshall (University of Antwerp & University of Copenhagen) and colleagues address the challenge of translating contemporary astrophysics research topics into teaching materials for

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[1] https://indico.cern.ch/category/15165/

secondary school students. Marshall draws on conceptual metaphor theory to study the educational potential of hands-on experiments as physical analogies for exoplanets.

Paul Alstein (Utrecht University) and colleagues address the challenge of teaching the abstract and counterintuitive phenomena of special relativity by creating a simulation-based inquiry learning environment. Alstein draws on the lesson study approach to foster active collaboration between researchers and teachers in developing the learning environment that invites secondary school students to model relativistic effects.

Urban Eriksson (Uppsala University) and colleagues address the challenge of understanding and communicating spatiotemporal scales in the universe, identified as threshold concepts in physics education. Given students' challenges to 'see' beyond immediate experiences, Eriksson adopts social semiotic theory to identify experts' strategies when reasoning across scales. He argues that these strategies can improve undergraduate and teacher education programs.

Jyoti Kaur (University of Western Australia), as part of the Einstein-First project, addresses the challenge of introducing modern physics concepts to primary school students. Challenging the traditional view that quantum physics and relativity are strictly for older students, Kaur draws on role-play and hands-on activities to tailor instructional approaches to the specific needs of young learners.

Conclusion

In conclusion, this symposium unites diverse research efforts under the IMPRESS initiative to collectively enhance the teaching and learning of modern physics. By addressing the inherent abstraction and intangibility of the field’s concepts, the four contributions offer innovative instructional approaches for learners from primary to tertiary education.

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IMPRESSions of the Invisible

The Uses of Hands-On Experiments as Physical Analogies

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This project is based on a set of inquiry lessons that use hands-on experiments to teach about exoplanet clouds and lightning in secondary schools (ages 16 - 18). The experiments act as models, specifically physical analogies, of the weather phenomena in question. For this study, students (n=28) participated in audio-visually recorded lessons and peer-led group interviews. The findings provide insight into the uses of the experiments as physical analogies during student discussion. It is found that students can critically assess the experiment's applicability to the phenomena and can use the analogies to aid in both information seeking and sharing.

Introduction

Models are a staple in science teaching and learning as they can help to convey and discuss abstract concepts by comparing them to something that is more tangible or familiar. There is ample existing research into the use of metaphors and analogies as models in the classroom, the majority of which focus on the verbal aspects of these. However, it is also possible for these models to be enacted physically. In this study, we investigate the use of hands-on experiments as physical analogies, where students will interact with and manipulate the experiment themselves. The aim of this study is to observe and analyse the ways in which students talk about these experiments as physical analogies. The research questions for this project are: 1) In which ways do students utilise the experiment as an analogy during discussion? 2) How do the physical limitations of an experiment as an analogy impact the way that students discuss the concepts in this experiment?

Theoretical Framework

This study builds on conceptual metaphor theory [1], thinking of physical analogies as a multimodal instance of conceptual metaphor. In this study, we will consider hands-on experiments in inquiry-based science lessons [2] as physical analogies. Analogies work by utilising a ‘target domain’ and a ‘base domain’ [3]. The target domain is the (more abstract) topic or subject that we wish the students to be able to understand, and the base domain consists of experiences and ideas that students already have access to. Through analogies, we explicitly map aspects of the base domain onto the target domain in order to aid students' understanding of a subject.

Methods and Findings

This study is part of a PhD project that is focused on the translation of contemporary astrophysics research topics into teaching materials. We developed a set of lessons that use hands-on experiments to teach students about clouds and lightning on exoplanets. We tested these lessons with two groups of students aged 16 to 18 (n=28). After the lessons, the students participated in peer-led group interviews. We audio-visually recorded each student group and analysed the resultant data using thematic analysis [4] and systematic metaphor analysis [5]. The findings from this study show that the experiments in these lessons were utilised by students as physical analogies in multiple distinct ways during discussions. A breakdown of these ways can be seen in Table 1.

	Finding	Example Data Excerpts
1	Students could map aspects of the base domain onto aspects of the target domain.	S1: “The cold water at the top of the jar could be like the outer cold atmosphere…” S2: “Yeah, and then the hot water at the bottom could be like the heat from the earth, like the surface of the earth is warmer”
2	Students could identify elements of the base domain that did not map to the target domain	S1: “I guess the dish soap is kind of irrelevant to experiment itself, because the only thing it did was to help us visualize the experiment”
3	Students were seen to switch between the target and base domains when explaining the concept	S1: “There are two clouds – one is very positive and one is very negative” S2: “No… it was more like they split up, like with the metal container, the bottom got negative and the top got positive”
4	Students could use the base domain as a refence point to seek clarification in respect to the target domain.	S1: “I don’t know how the hairspray works? Was that a…” S2: “no, that was a… um… aer…” S1: “aerosol?” S2: “yeah, so the little dust stuff.”

[Table 1. A summary of how students used the experiments as analogies during discussion.]

Conclusion

These findings suggest that students, after using a hands-on experiment in a lesson, will be able to discuss the topic of the lesson using the experiment as an analogy. Students are able to map the relevant aspects of the experiment to the relevant aspects of the topic they are learning during discussion, and in addition to this, they are able to identify which aspects of the experiment do not correlate to the topic they are learning about and are present purely for practical purposes. We observed the students using aspects of the analogy as a way to ask for clarification about the topic and were able to switch relatively seamlessly between aspects of the experiment and the relevant aspects of the scientific topic. This suggests that using experiments as analogies for abstract scientific concepts in a lesson can provide a shared experience and, therefore, a shared ‘language’ between students that can aid students in both sharing and seeking knowledge.

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Supporting secondary school students’ understanding of special relativity through simulation-based inquiry learning

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Abstract. The theory of special relativity is a notoriously challenging learning objective in secondary school physics. While special relativity requires a different mode of thinking about measurement, there is no possibility to perform relativistic measurements in practice. We have designed a simulation environment in which students can explore relativistic phenomena by modelling virtual relativistic experiments. A team of researchers and secondary school physics teachers collaboratively designed, taught, observed and evaluated a 90-minute introductory lesson in which students performed inquiry-based simulation assignments. Preliminary results indicate that this approach helped students to explicate pre-existing assumptions and to reflect on them critically.

Introduction

While Einstein’s theory of Special Relativity (SR) is considered one of the most iconic topics in modern physics, it is widely recognised as a challenging learning objective in secondary school physics [1]. Relativistic effects, such as time dilation, are very remote from everyday experience. Additionally, learning SR requires students to adopt an operationalisation of measurement that is different from the common use of measurement in practical experiments.

Rather than performing practical experiments, the conceptual nature of SR may be explored by performing virtual experiments. For this purpose, we have developed a simulation environment called *Relativity Lab*, in which students can construct and observe simple relativistic experiments [2]. A screenshot of *Relativity Lab* is shown in Figure 1. *Relativity Lab* was designed to run relativistic simulations, with relative velocities approaching the speed of light, as well as non-relativistic simulations. Moreover, students are able to view the simulation from multiple inertial frames so that comparison of measurement outcomes in different inertial frames is possible.

We report on the implementation of *Relativity Lab* in a 90-minute introductory lesson. The lesson was co-created by a team of researchers and secondary school physics teachers, following the research approach of Lesson Study. By close observation of eight case students, we answer the following research question: how can students’ understanding of time dilation be supported by simulation-based inquiry learning?

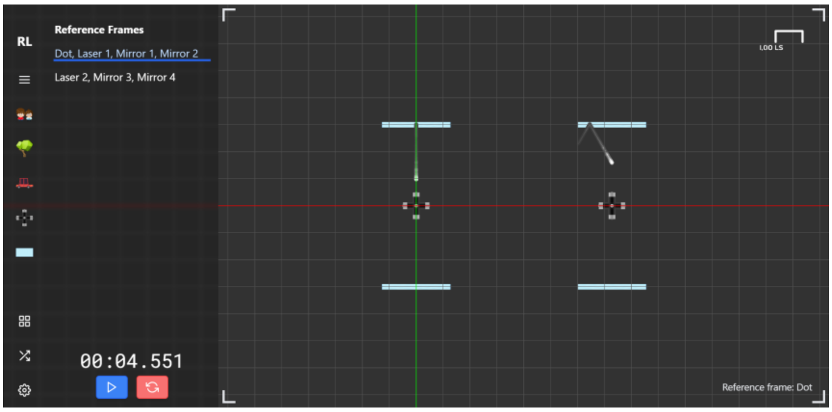

Fig. 1. A simulation of time dilation of a light clock in *Relativity Lab*. In the currently selected inertial frame, the left light clock is stationary while the right light clock is moving. The period of the moving light clock is dilated.

Method and lesson design

In order to relate to educational practice as closely as possible, we chose to apply the research approach of Lesson Study (LS). Our LS team consisted of three science education researchers (the authors of this abstract) and three physics teachers from two Dutch secondary schools.

In five online design meetings, the LS team designed a 90-minute introductory lesson that includes two inquiry-based simulation assignments as well as a plenary discussion of two foundational concepts: frames of reference and the light postulate. A learning trajectory was outlined by identifying eight key activities that were planned throughout the lesson.

The research lesson was performed twice by two of the LS team members. During both research lessons, the remaining team members observed four case students who had been selected on the basis of capacity and confidence. Post-lesson student interviews and evaluations with the LS team after the first research lesson resulted in improvements for the second research lesson.

Findings and conclusion

Preliminary analysis of the data indicates that each of the observed student pairs followed a unique learning trajectory, occasionally matching the predefined learning trajectory. The simulation assignment focusing on non-relativistic motion was successfully performed by all of the students. This indicates that the case students had no difficulties in describing relative motion in terms of inertial frames. It was clearly evidenced that the simulation assignments prompted students to explicate their pre-existing assumptions about relative motion. In the following example a student refers to a train wagon in which a ray of light is emitted: *“In principle, the wagon is just something by itself and the [observers] are standing inside of it, so the fact that it moves should not matter, right?”*. Observing the simulation helped students recognise discrepancies in their prediction: *“This is not what we expected at all. (...) When we thought about [the experiment], we viewed it from the laser, where everything is standing still, but now we see that everything moves to the right.”*

Six out of eight case students misinterpreted the plenary discussion of the light postulate. Consequently, they did not correctly apply the light postulate in the relativistic simulation assignment. This led to misinterpretations of time dilation of light clocks. Four case students overgeneralised the invariance of the speed of light to the invariance of time intervals. Students incorrectly associated the time dilation of a light clock with the light clock’s direction of motion or with the time required for light to travel from the light clock to an (imaginary) observer. Each of the students who had predicted the time dilation of light clocks incorrectly recognised the flaw in their prediction after observing the simulation. However, they could not always provide an explanation of the simulation’s outcome. From this, it can be concluded that a stronger emphasis on foundational concepts, such as the light postulate, is required for students to gain conceptual understanding from the simulation assignments. In our upcoming study, we expanded the introductory lesson into a series of three lessons, focussing on the representation of the observed simulations in spacetime diagrams and the mathematical expression of time dilation.

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The SCALE of it all: On disciplinary meaning-making and communication of large and small spatio-temporal scales.

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Abstract. Coming to understand and make meaning of the Universe in all its spatio-temporal scales is known to be difficult for almost everyone entering science, regardless of age and educational level and referred to as a threshold concept in the literature for understanding the universe on a deeper level. We have investigated experts' ways of communicating scales and present results on the different strategies identified in their disciplinary communication. These experts use a variety of strategies depending on their disciplinary belonging. These strategies may have a bearing on undergraduate education, in particular teacher education, to address issues when learning science.

Introduction

A hallmark of much of scientific practice is the necessity of dealing with phenomena that are much larger or much smaller than oneself. This presents scientists and students of science with an ever-present perspectival challenge to 'see' beyond their immediate experiences in non-experienceable spatial scales, usually by proxy of data collected with scientific instruments and/or the depictions of scientific visualisations. However, despite the near ubiquity of unfamiliar spatial scales inside and outside the doing/teaching/learning of science, remarkably little has been done to investigate how people come to make meaning and communicate spatial and temporal scales and which types of teaching interventions can best support learning in this interdisciplinary area [1]. We have previously conducted a pilot study on experts in space physics where various strategies for communicating meaning-making were identified [2]. Our present study approaches awareness of spatial scales from the perspective of spatial size *per se* and will examine how experts´ knowledge in one spatial domain can be transferred into other domains. These topics are severely under-researched as of now but identified as difficult for understanding science (e.g., [1; 3]).

Theoretical Framework, research and research questions

The theoretical framing of our project draws on *Social Semiotic in University Physics Education* [4] in general and, in particular, on Eriksson's recent research and theoretical contributions to social semiotics [3; 5; 6].

Based on the above, we aim to address the following research questions:

RQ1: -*What are the qualitatively different strategies experts use for meaning-making and communicating spatial scales?*

RQ2: -How do the experts convey their experience of spatial scales during engagement with their peers?

Methods and findings

This study is predicated on an exploration of how science students experience spatial scales inspired by combining social semiotics and variation theory of learning [6], which can be considered amongst the family of inductive analytic frameworks that endeavour to examine what emerges from the data itself rather than from the application of an existing theory. Data collection comprised video recordings of participants while they completed a ranking task for objects ranging in size from a Proton to the Universe. From this, we have derived a set of qualitatively different strategies for experiencing and communicating spatial scales.

The data analysis is still ongoing, and we will present the final results at the conference. However, the preliminary analysis has revealed that the experts in molecular biology use similar strategies for meaning-making and communication as space physics experts did [2][2], with one important exception: the molecular biologists did not use scale as a concept, neither linear nor logarithmic. Instead, they used a direct comparison between the objects. However, they performed equally well on the ranking task as did the space physicists that we have studied and reported on previously.

Conclusions

From the study we have performed, we find that the experts in molecular biology use strategies similar to those of the experts in space physics [2], but with one important exception: logarithmic scales. Besides this, we find that both groups use various strategies to make meaning and communicate the spatial scales of the objects. The ranking task was a real challenge when it came to communicating and explaining how big or small a particular object is in relation to another (cf. [1]). The main difference between this expert group and the previous one was that the molecular biologists did not use the real size of the objects in their discussions but rather compared them or discussed how they were related. More interesting results will be presented at the conference.

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[2] Strategies identified in an earlier study [2] (subcategories for each of these strategies in parentheses): Anchoring (Object or Number), Analogies (Utilising or Resisting), Scales (Linear or Logarithmic), Representation usage (Representations as symbols or as pictures), and Relating objects Nestedness of objects, interaction of objects, or calculations).

First Trial of Teaching Einsteinian Physics to 7–8-Year-Olds

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Abstract The decline in student interest and performance in science has sparked concern. To address this, the Einstein-First project aims to make science more engaging by introducing Einsteinian concepts early on. After successful trials with 11-15-year-olds, this article reports the first study on 7-8-year-olds' understanding of Einsteinian concepts. Two Year 3 (age 7 – 8) classes participated, one with significant in-class revision. Results show a substantial uptake of Einsteinian concepts, with increased positive attitudes in both classes. However, the contrast in learning outcomes underscores the importance of teacher reinforcement. This study suggests that 7-8-year-olds can grasp key Einsteinian concepts, but longer programs are needed for consolidation.

Introduction

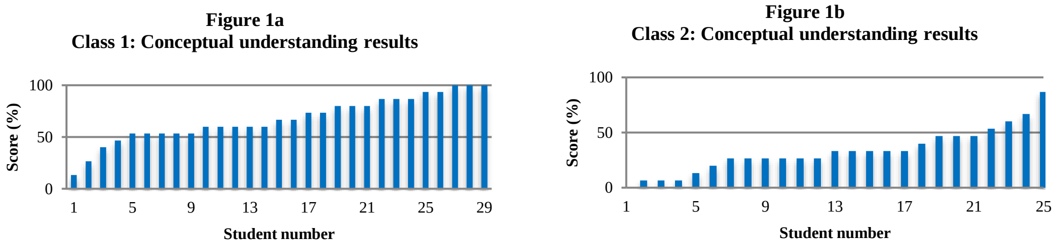
There is a growing interest among science educators and researchers in introducing Einsteinian physics to school students at earlier ages. This interest arises not only from the fact that Einsteinian physics gives the best understanding of physical reality but also from its direct relevance to the workings of modern devices. For over a decade, the Einstein-First project in Australia has been developing hands-on teaching approaches for introducing Einsteinian physics to school students. Following successful trials with students aged 11-15, this article reports the first study on the ability of 7-8-year-old students to understand Einsteinian concepts. This trial followed the six principles of Einstein-First: 1) Introduce concepts through activity-based group learning, 2) Use toys, models, and analogies, 3) Promote whole-body learning, 4) Use appropriate language and keywords for unifying concepts, 5) Draw on role plays for representing conceptual change and human endeavour and 6) Use only inexpensive consumer-level equipment (Kaur et al., 2024).

This article addresses the persistent decline in student interest and performance in science, emphasising the crucial stages of upper primary and lower secondary education. Research indicates that early engagement in science is vital for positive trajectories, yet students often find school science irrelevant and boring (Barmby et al., 2008). The article advocates for the introduction of modern science concepts, such as Einsteinian physics, at an earlier age, challenging the assumption that these concepts are too difficult for children to understand. The importance of hands-on teaching approaches, including role-play, is emphasised to make abstract science more interactive and engaging for students. The ultimate goal is to reverse declining interest by aligning school science with current scientific research and providing students with exciting, relevant learning experiences.

The study is guided by the research question, "How do Year 3 students respond to learning Einsteinian physics concepts when presented with hands-on teaching approaches?"

Methods and findings

Two Year 3 classes (age 7-8) of nominally matched aptitude but with different teaching circumstances participated in the program. Nine lessons were delivered to both classes over four weeks, covering topics such as curved space, curved space geometry, photons, interference, and diffraction. Each topic was presented through hands-on and role-play activities as a way to make abstract concepts more approachable for this age group. The data was collected through pre- and post-conceptual understanding questionnaires, as well as attitudinal questionnaires. The conceptual understanding results of Class 1 and Class 2 are presented in Figure 1a and Figure 1b. In the pre-test, students' responses indicated no prior knowledge of Einsteinian concepts (as generally expected), and many gave no answers at all. For this reason, we recorded zero scores for all pre-tests.



Figures 1a and 1b. Conceptual understanding post-test results for Class 1 and Class 2 students, arranged in ascending order.

As shown in the figures, there is a significant improvement in students' conceptual understanding across both classes. However, Class 1 performed exceptionally well due to the teacher's involvement. Alongside the improvement in students' conceptual understanding, we observed that both classes struggled to comprehend the concept of gravity; however, they demonstrated a strong understanding of light as photons and experimental geometry on curved surfaces. Our programs aimed for gender neutrality, and after conducting brief data analysis, we observed no gender differences in students' attitudes toward learning Einsteinian science through hands-on teaching approaches, as anticipated.

We identified several limitations during these trials. It was the team's first attempt at teaching students aged 7–8, and we lacked prior experience in this age group. The presenters assumed certain pre-existing understandings, such as the assumption that students were familiar with measuring angles for the curved space geometry activity. Another limitation was insufficient attention to language, particularly in giving students the necessary time to absorb new vocabulary, such as words like 'momentum' and 'photon'. Students at this age face limitations in reading and writing, and many are hindered by the complexity of written language. This experience led us to create multiple-choice and pictorial form questions.

Conclusion

Through our initial trials with 7-8-year-olds, we learned valuable lessons in teaching Einsteinian physics to younger students. It became evident that introducing the language of modern science to this age group is achievable. Consequently, based on these trials, we have developed and implemented a continuous spiral curriculum spanning ages 7-15, known as "Eight Steps to Einstein's Universe," which is currently being trialled in over 50 schools across Australia.

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