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VISUALIZATION OF THOUGHT EXPERIMENTS IN SPECIAL RELATIVITY EDUCATION AT THE SECONDARY LEVEL

Special relativity theory (SRT) presents an attractive introduction to modern physics in secondary education. Understanding the principles of SRT, however, requires a conceptually demanding learning process, involving a variety of robust learning difficulties. Thought experiments (TEs), performed by students themselves, provide a fruitful learning tool to address these difficulties. We present two visualization tools that explicitly support students in performing specific phases of a TE: a computer modelling tool and a paper and pencil representation of space time. We discuss relevant design features and specify how these visualization tools can be used to address learning difficulties.

Keywords: Physics, Secondary School, Design Based Research

INTRODUCTION

There is currently a growing international interest in introducing special relativity theory (SRT) into secondary education (Choudhary et al., 2019). Representing a radical departure from classical physics, SRT can be an attractive introduction to modern physics. Learning about the differences between classical and modern physics may support a better understanding of theory development in science (Levrini, 2014).

SRT replaces the classical notion of space and time as separate entities by the notion of a unified spacetime. This results in counter-intuitive consequences, such as the relativity of simultaneity, time dilation and length contraction. Understanding these relativistic phenomena requires a firm understanding of the principles on which they are based: the postulate of special relativity and the postulate of invariant light propagation, as well as prerequisite knowledge about the use of reference frames. This learning process, however, has proven to be notoriously difficult, especially at the level of secondary education. A recent literature review (Alstein et al., 2020) has identified a variety of student conceptions, and it is argued that these conceptions form a source of robust learning difficulties.

Thought experiments (TEs) present a possible solution to this problem, as they allow students to explore the consequences of relevant concepts in an idealised world (Velentzas & Halkia, 2013). In the initial phase of a TE, the thought experimenter poses a central question, defines the theoretical basis and describes what the setup of the TE looks like. In the second phase, the outcome of the TE is obtained through deductive reasoning with the theoretical principles of the initial setup. In the third and final phase, the thought experimenter reflects on the process and formulates generalized implications (Reiner & Burko, 2003). Because students reason with a 'what if' scenario while performing a TE, they are stimulated to communicate their ideas. This can support students to overcome conceptual barriers and learn abstract concepts (Velentzas & Halkia, 2013).

Prior research indicates that visualization of TEs plays an important role in supporting students' learning process. However, the way that TEs are often illustrated limits students' interaction with the TE and therefore does not stimulate students to perform the TE themselves (Horwitz & Barowy, 1994; Kamphorst et. al., in press). Here we present two visualization tools that do support student reasoning while performing a TE. We will also discuss some design features that made this possible.

EXAMPLE 1 – MODELLING AND SIMULATION TOOL

In the first phase of a TE, the thought experimenter constructs a setup based on a central question. Many of the TE setups in SRT are difficult to imagine, as they require students to create mental imagery of the trajectories of relatively moving bodies as seen from different reference frames. Moreover, it has proven to be difficult for students to conceptualize reference frames and to apply the principle of relativity. In particular, students often ascribe a special status to the reference frame of the Earth. Novel visualization techniques may offer a fruitful first step in resolving the reported learning difficulties. A number of realistic virtual environments and serious games have recently been developed (Alstein et al., 2020). However, the level of interaction with these virtual environments is often limited to pre-programmed visualization of relativistic phenomena. We report on the design of an exploratory modelling and simulation tool that allows students to model and simulate TEs themselves.

In the proposed modelling and simulation tool, students are able to model TEs by placing virtual objects (such as cars or trains) onto a two-dimensional grid and assign velocities to each object relative to the currently active reference frame, as shown in a first prototype in Figure 1 (left). Running the simulation presents students with a visualization of the trajectories of the objects as seen from the currently active reference frame. By switching between any of the available reference frames, students are able to explore transformations of trajectories and velocities in the non-relativistic limit. At velocities near the speed of light, students are able to explore TEs that involve the relativity and simultaneity and time dilation.

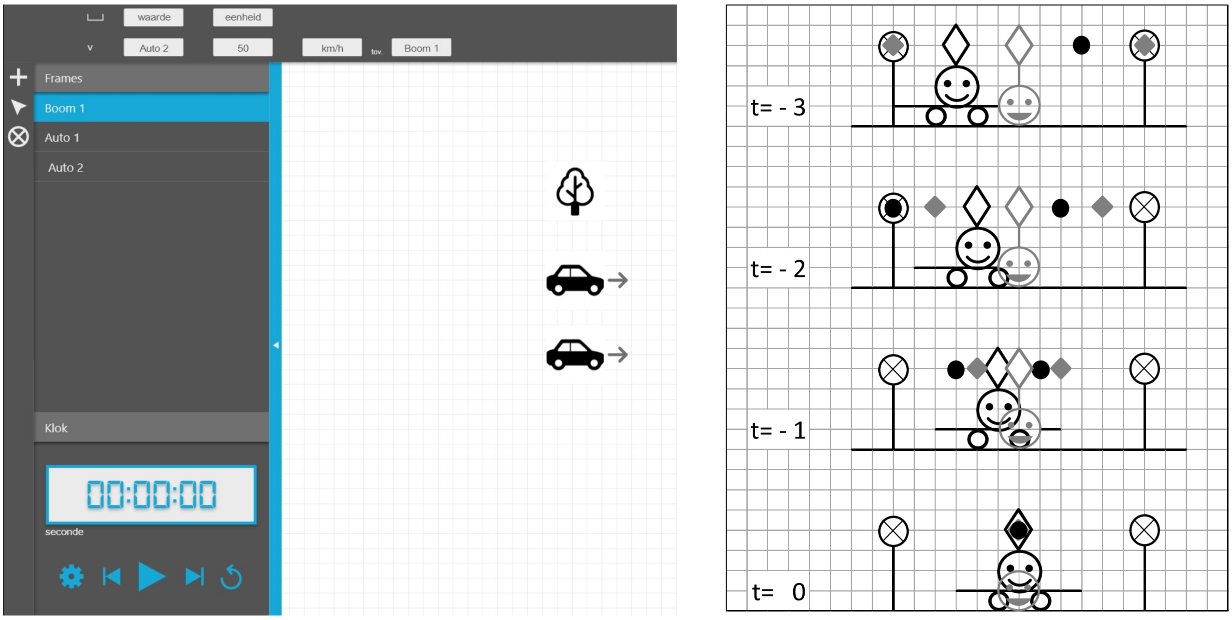

Figure 1 (left). A digital prototype of the modelling and simulation tool. In this model, the velocities of two cars are assigned relative to the reference frame of a tree.

Figure 1 (right). Event diagram showing the position of objects, observers, and events for four subsequent moments in time. The two lamps are represented by the circuit symbols. Observer A is in relative movement to the lamps on his skateboard with a speed of one square per time step to the right. The diamond shape represents the measuring device registering two light flashes arriving simultaneously at the observer when he is midway between the lamps. Observer B is at the same position at t=0 and is at rest relative to the lamps. Light propagation is drawn in the ED for observers A (black circles) and B (grey diamonds) respectively.

Basic design principles were formulated based on a literature review, student interviews and classroom observations. One of the main design features is that reference frames are represented as layers, each layer corresponding to the set of objects that are in rest in that reference frame, so that there is no necessity for a (separate) observer. We hypothesize that this level of abstraction helps students to recognize that frames of reference should not be associated with any particular observers or events.

EXAMPLE 2 – EVENT DIAGRAMS

Reasoning with the light postulate appears notoriously difficult to learn. Even after instruction, students of all levels can only recite the light postulate. Prior to instruction, secondary students either reason with a constant speed of light relative to the light source or relative to an absolute space (Kamphorst et. al., 2019). A task design based on TEs supported by Event Diagrams (EDs) can address this issue.

EDs support students to reason with light propagation and communicate their light propagation model. An ED shows the position of objects and events at several moments in time, from a specific reference frame. By adding two features, we redesigned the ED to make it an instrument for student reasoning. First, the ED is drawn on a grid, making it easier to identify positions and measure distances. Second, we show a series of pictures that show a sequence of events at regular time intervals (time units) (Kamphorst et. al., in press).

In our task, students are presented with the setup of the TE and a central question. Figure 1 (right) shows the position of a cart with two lamps attached and an observer with a measuring device. At the bottom snapshot an event is shown: two light flashes arriving simultaneously at an observer. Students perform the second phase of the TE themselves. They are asked to figure out at what times the two lamps emitted their light flashes for each of the two observers. Students do this by drawing the position of the light flashes in each picture of the ED. Students are given the freedom to choose their theoretical basis to perform the TE. They can either use the light postulate or fall back to a pre-instructional light propagation model (Kamphorst et. al., 2019). To perform the deductive reasoning and obtain the outcome of the TE, the speed of light needs to be adapted to make sense in the context of the ED. We have set the speed of light at two squares per time unit. Supported by the visualization of the ED, students perform the deductive reasoning process of the TE themselves. With some additional support by a teacher, students can also reflect on the general implications of the outcome of this TE: the lamps emitted the light flashes simultaneously for observer A, but not for observer B. Therefore, simultaneity is observer or reference frame dependent (Kamphorst et. al., in press).

As all visualizations, EDs are a limited representation of the physical world. With carefully designed tasks, students are given the conceptual tools to reflect on those limitations. ED's can be used as an introduction to the more abstract representation of the Minkowski diagram as well.

CONCLUSION AND OUTLOOK

We have presented two visualization tools that support student reasoning while performing TEs: one using computer modelling and one using paper and pencil. A central principle of both visualization tools is that students are required to perform at least one of the three phases of a TE themselves. This results in a higher level of engagement as compared to more traditional presentations of TEs.

Note that the two visualization tools are complementary. With the computer modelling tool, students can explore changes in trajectories and velocities across reference frames. This allows them to observe naturally that the laws of physics remain the same in each inertial reference frame. With EDs, students can apply their understanding of reference frames to light propagation. Students can explore the difference between the light postulate and their pre-instructional models of light propagation and derive the consequences of the light postulate themselves.

REFERENCES

Choudhary, R., Kraus, U., Kersting, M., Blair, D., Zahn, C., Zadnik, M., & Meagher, R. (2019). Einsteinian Physics in the Classroom: Integrating Physical and Digital Learning Resources in the Context of an International Research Colleboration. *The Physics Educator, 01,* 1950016. https://doi.org/10.1142/S2661339519500161

Levrini, O. (2014). The role of history and philosophy in research on teaching and learning of relativity. In M. R. Matthews (Ed), *International Handbook of Research in History, Philosophy and Science Teaching* (pp. 157-181). Dordrecht: Springer.

Alstein, P., Krijtenburg-Lewerissa, K. & van Joolingen, W. R. (2020). Teaching and learning special relativity theory in secondary and lower undergraduate education: A literature review. *ArXiv e-prints, arXiv:2011.08059 [physics.ed-ph].*

Horwitz, P. & Barowy, B. (1994). Designing and using open-ended software to promote conceptual change. *Journal of Science Education and Technology, 3,* 161.

Reiner, M., Burko, L.M. (2003). On the Limitations of Thought Experiments in Physics and the Consequences for Physics Education. *Science & Education, 12,* 365–385. https://doi.org/10.1023/A:1024438726685

Velentzas, A., & Halkia, K. (2013). The use of thought experiments in teaching physics to upper secondary-level students: Two examples from the theory of relativity. *International Journal of Science Education, 35(18)*, 3026-3049. https://doi.org/10.1080/09500693.2012.682182

Kamphorst, F., Savelsbergh, E., Vollebregt, M., & van Joolingen, W. (in press). Event diagrams - supporting student reasoning in special relativity thought experiments. In D. Blair, & M. Kersting (Eds.), Teaching Einsteinian Physics in Schools. Taylor & Francis.

Kamphorst, F., Vollebregt, M. J., Savelsbergh, E. R., & van Joolingen, W. R. (2019). Students' pre-instructional reasoning with the speed of light in relativistic situation. *Physical Review Physics Education Research, 15,* 20123. https://doi.org/10.1103/PhysRevPhysEducRes.15.020123