Opinion Piece: Following in the Footsteps of Einstein: Modernising Physics Education Using History and Philosophy of Science

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Creating a new theory is not like destroying an old barn and erecting a skyscraper in its place. It is rather like climbing a mountain, gaining new and wider views, discovering unexpected connections between our starting points and its rich environment. But the point from which we started out still exists and can be seen, although it appears smaller and forms a tiny part of our broad view gained by the mastery of the obstacles on our adventurous way up. (Albert Einstein & Leopold Infeld, 1938)

The case for Einsteinian physics education

Albert Einstein changed a whole generation's scientific and philosophical worldview in one impressive stroke of intellectual prowess. By linking the physics of gravity to the mathematics of curved spaces, Einstein demonstrated one of the most remarkable feats of human thinking - and propelled 20th-century physics into its modern era. From the big bang to black holes, from cosmology to gravitational wave astronomy, the theory of relativity has inspired awe and wonder among scientists and the general public alike.

In February 2016, the LOGO Scientific Collaboration announced the first direct observation of gravitational waves (figure 1). Shortly after, the Nobel Prize committee awarded the 2017 physics prize 'for decisive contributions to the LIGO detector and the observation of gravitational waves," positioning the theory of general relativity at the forefront of research.

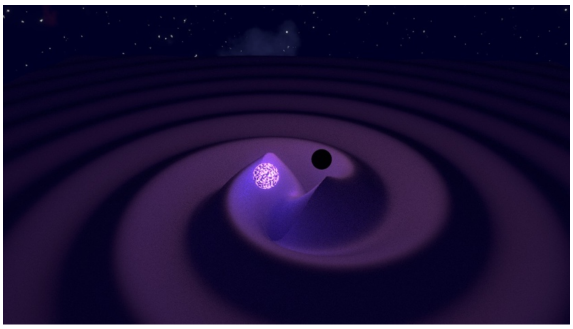

Figure 1 – General relativity describes the dynamic interplay between space, time, and matter. This visualisation depicts a binary system of a black hole and a neutron star and the gravitational waves that

ripple outward as the two objects spiral toward each other. (Credit: Mark Myers/Ozgrav, https://www.ozgrav.org)

In 2019, the first image showing the shadow cast by a black hole confirmed yet again general relativity and opened a new era of astrophysics (Akiyama K. et al., 2019). More than one century after Einstein presented the theory of relativity, his ideas seem more popular and relevant than ever.

Nevertheless, to most people nowadays, Einstein's ideas still seem as challenging as they did 100 years ago when Bertrand Russell observed that a 'certain effort of imaginative reconstruction is unavoidable' if we are to understand the theory of relativity (1925, p. 9). Most children today continue to grow up with notions of classical physics. In many countries, students hardly ever come across modern concepts of space and time in the classroom. Instead, it is left to science popularisers, outreach practitioners, or enthusiastic teachers to teach students our current best understanding of the world outside of the regular physics lessons.

Employing history and philosophy of science in the service of physics education can serve as a successful approach to making Einstein's ideas more accessible and foster motivation among young learners (Henriksen et al., 2014; Kersting & Blair, 2021; Levrini, 2014; Stadermann & Goedhart, 2021). In fact, historical contextualisation and philosophical perspectives provide many instructional opportunities to help students on their adventurous climb up the mountains of Einsteinian physics to let them gain new vistas and discover unexpected connections between science and society.

In the following, three such opportunities are presented in the context of general relativity education. These opportunities were developed within ReleQuant, an educational project in Norway that pooled the expertise of physicists, physics education researchers, physics teachers, and educational designers to develop digital learning resources and study students' learning processes and motivation in Einsteinian physics (Henriksen et al., 2014). Parts of this essay are adapted from the ReleQuant PhD thesis 'General Relativity in Secondary School' (Kersting, 2019).

Instructional opportunity 1: focus on the evolution of physics and the nature of science

Often, general relativity is presented as a revolutionary new way to describe gravity, space, and time. Consequently, many educators argue that students must go through ontological conceptual changes to cope with the 'radical shift to the Einsteinian paradigm' (Kaur et al., 2018, p. 2506) and that instructional strategies should aim to soften the impact of a counter-intuitive theory (Holton, 1973; Levrini, 2014). However, research suggests that emphasising the radical break between classical and Einsteinian physics might not be the best instructional approach in general relativity education. For example, upper secondary school students in Norway felt baffled or bewildered that much of what they previously had learned about gravity, space, and time was outdated knowledge (Kersting et al., 2018). Instead of focusing on the differences between classical and Einsteinian physics, it might be more fruitful to show the continuity in thought and practice that underlay the evolution from 19th-century physics to our modern understanding (Kim & Lee, 2021).

Here, Einstein's conception of the evolution of physics provides a valuable starting point. For Einstein, knowledge of the history of physics is valuable because such knowledge emphasises the connections between new ideas and their rich conceptual environments (Einstein & Infeld, 1938). Although the theory of relativity gives us a new physical and philosophical vantage point from which to view reality, this vantage point is not divorced from previous physical methods. Einstein's thinking followed assumptions that have long guided scientific practice: simplicity, harmony, and universality (Kim & Lee, 2018).

Einstein built on core ideas of Galileo's principle of relativity and Maxwell's theory of electromagnetism to revise our understanding of space and time, consistent with existing physical laws. Rather than seeing the theory of relativity as a radical and fundamental break with classical physics, its development illustrates a rigorous scientific practice that examines physical assumptions together with all its implications carefully.

Einstein's ideas are, thus, an excellent opportunity to discuss the nature of science and the way scientific knowledge progresses. Science is a process of building models to explain observations and then refining those models through careful thought and experimentation. Good models explain existing observations and make testable predictions. Although Newton's force model might seem intuitively correct, it does not describe all experimental observations. Educators argue for the re-education of our intuitions to make them compatible with what seems to be the best science around (Chandler, 1994). Helping students build awareness of the scope and limitations of physical theories and showing how general relativity extends classical physics can be one step towards such a re-education (figure 2).

Figure 2 – This instructional approach emphasises the continuity between Newtonian and Einsteinian physics and shows how general relativity extends Newton's law of motion. The screenshot is taken from the digital learning environment General Relativity that is freely available at www.viten.no/relativity.

Besides, our society's collective fascination with Einstein can act as a fruitful entryway to teach and reflect on the nature of science. Einstein is a popular figure in contemporary culture, and students in the ReleQuant project repeatedly mentioned that they enjoyed learning more about Einstein (Kersting et al., 2018). The students appreciated a depiction of Einstein as a person who struggled and had to work hard to find a new theory of gravity. Following some of Einstein's historical struggles helped students relate to Einstein's reasoning and build a qualitative understanding of general relativity. These findings align with previous research on story-based instructional models that improve student motivation and academic performance if the models show how scientists like Einstein made achievements through failures and struggles (Lin-Siegler et al., 2016).

Instructional opportunity 2: develop imagination in physics education

There is no doubt that Einstein was a highly original thinker with a penetrating mind and a boundless imagination. Indeed, Einstein stated that:

> Imagination is more important than knowledge. For knowledge is limited, whereas imagination embraces the entire world, stimulating progress, giving birth to evolution." (Einstein as quoted in Viereck, 1929)

Einstein's vivid imagination shed light on physical problems, often in the form of thought experiments. He chased beams of light, sent flashes of light off moving trains, or considered a person in free fall. Indeed, many of the fundamental principles in the theory of relativity sprung from famous thought experiments. Einstein used these thought experiments to elucidate physical phenomena and convey key ideas in simple terms. Doing so, he was keenly aware of the importance of honing one's imagination to make discoveries:

> If you wish to learn from the theoretical physicist anything about the methods which he uses, I would give you the following piece of advice: Don't listen to his words, examine his achievements. For to the discoverer in that field, the constructions of his imagination appear so necessary and so natural that he is apt to treat them not as the creations of his thoughts but as given realities.' (Einstein, 1933, pp. 5–6)

The history of physics abounds with examples of thought experiments and remarkable imaginative accomplishments (Asikainen & Hirvonen 2014; Kind & Kind, 2007). But it is not only in hindsight that imagination becomes apparent in scientific practice. Today, many scientists acknowledge that imagination plays a significant role in their work (Osborne et al., 2003). Despite this acknowledgement, science education researchers still have little understanding of the role of imagination in the science classroom – or how imagination can be developed through instructional activities (Steier & Kersting, 2019).

General relativity education presents a fascinating opportunity to study the role of imagination in students' learning processes. Relativistic concepts challenge students' everyday experiences and seem to contradict lessons from classical physics. Thus, students need to perform a considerable imaginative effort to overcome their experiential understanding of gravity, space, and time to understand Einstein's spacetime description (Steier & Kersting, 2019). In particular, secondary school students' imaginative struggle to articulate and conceptualise the notion of spacetime reveals a conceptual tension between Newtonian and Einsteinian frameworks (figure 5).

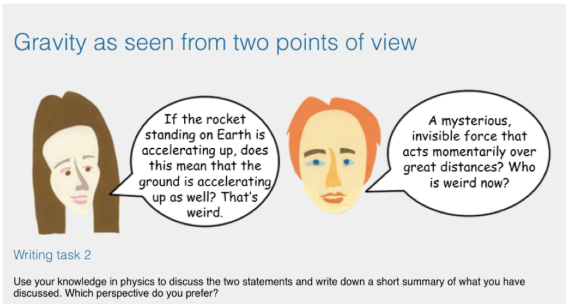

Figure 3 – In this task, students discuss gravity from two perspectives to build awareness of the two conceptual frameworks that Einstein and Newton proposed to describe gravitational phenomena. The tension between these frameworks and shifting between them presents students with imaginative challenges. The screenshot is taken from the di-

gital learning environment General Relativity that is freely available at www.viten.no/relativity.

Research in ReleQuant identified various (meta-)imaginative actions that students performed to make sense of this tension and shift fundamental assumptions about the nature of space, time, and gravity (Steier & Kersting, 2019). These actions comprised bodily and gestural depictions, sketches, analogies, and new imagined scenarios. Importantly, these actions built on each other as layers of meaning, and students shifted between these layers as they confronted their own imagination and limitations thereof. It seemed as if metaimagining (i.e. the ability to manage shifts between one's imaginative actions) was required to crosswalk different conceptual frames that entailed different explanations for the same gravitational phenomena (Steier & Kersting, 2019).

Teachers and educators can introduce imaginative activities as tools for students. Such instruction can guide students in intentionally applying thought experiments, constructing new metaphors, or performing abstract ideas collaboratively when confronted with imaginative challenges. Additionally, it is important to recognise situations where conceptual frameworks are in tension and require integration. Recognising these situations as imaginative challenges allows for a more nuanced instructional approach than merely reducing the notion of curved spacetime to a difficult concept (Steier & Kersting, 2019).

Instructional opportunity 3: address the philosophical background of general relativity

The evolution of physics is, of course, closely related to the philosophy of physics. The development of general relativity did not merely provide impetus to the field of physics but prompted a period of great productivity in the philosophy of space and time (Reichenbach, 1928). Not least, this development led to the culmination of a century-long dispute on the nature of space and time (Kersting & Steier, 2018). This dispute reaches back to Newton and Leibniz, who debated the fundamental nature of space and time in the 18th century (Vailati, 1997). While Leibniz viewed space and time as relational, Newton posited that space and time were absolute entities. At the end of the 19th century, philosophers and scientists again challenged the prevailing view of absolute space and time (Mach, 1893; Poincaré, 1898). Against this backdrop, Einstein proposed four-dimensional spacetime as a replacement of static notions of space and time:

> It has often been said, and certainly not without justification, that the man of science is a poor philosopher. Why then should it not be the right thing for the physicist to let the philosopher do the philosophising? Such might indeed be the right thing at a time when the physicist believes he has at his disposal a rigid system of fundamental concepts and fundamental laws which are so well established that waves of doubt cannot reach them; but it cannot be right at a time when the very foundations of physics itself have become problematic as they are now. At a time like the present, when experience forces us to seek a newer and more solid foundation, the physicist cannot simply surrender to the philosopher the critical contemplation of the theoretical foundations; for, he himself knows best, and feels more surely where the shoe pinches. In looking for a new foundation, he must try to make clear in his own mind just how far the concepts which he uses are justified and are necessities. (Einstein, 1936, p. 349)

From his experience at the forefront of the development of modern physics, Einstein knew that having cultivated a philosophical habit of mind had made him a better physicist (Howard, 2006). Therefore, Einstein, who explicitly acknowledged the example of Ernst Mach, was a keen advocate of fostering explicit philosophical approaches to physics in the teaching of physics – an attitude that physics educators and teachers nowadays can adopt to promote direct engagement with the philosophy of science:

> I fully agree with you about the significance and educational value of methodology as well as history and philosophy of science. So many people today - and even professional scientists - seem to me like somebody who has seen thousands of trees but has never seen a forest. A knowledge of the historic and philosophical background gives that kind of independence from prejudices of his generation from which most scientists are suffering. This independence created by philosophical insight is - in my opinion - the mark of distinction between a mere artisan or specialist and a real seeker after truth. (Einstein, 1944)

Following Einstein's footsteps, teachers can highlight the historical dispute on space and time and its philosophical implications to introduce general relativity in their classrooms. Instructional approaches can also emphasise that modern physics poses questions for which physicists still have not found unambiguous answers. In focus group interviews, middle and secondary school students appreciated the philosophical and open questions that general relativity brought up (Kersting et al., 2021). These aspects of physics challenged traditional stereotypes of physics and seemed relevant to the students' lives.

Conclusion

According to Einstein, common sense is 'nothing more than a deposit of prejudices laid down in the mind prior to the age of eighteen' (Barnett, 2005, p. 58). While experiments have repeatedly confirmed Einstein's theories, physics education in schools continues to be dominated by a 19th-century point of view. Consequently, the theory of relativity still contradicts the common sense of many. Thus, it is a noble cause to teach students our current best understanding of the physical world and add Einsteinian physics to the intellectual equipment of young learners.

Topics of Einsteinian physics provide an excellent opportunity to move beyond traditional content-focused instruction and tie physics into our society. For example, the first direct observation of gravitational waves of two merging black holes has been called the discovery of the century, akin to Galileo's first turning of his telescope to the sky (Grimberg et al., 2019). This exciting time in physics and astronomy represents a critical opportunity to engage students with concepts of Einsteinian physics (Key & Hendry, 2016). Instructional approaches that use history and philosophy of science can help teachers and instructors bring Einsteinian physics into classrooms.

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