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OPINION

A case for conceptual approaches in general relativity education

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Abstract

Increasingly, topics of general relativity enter mainstream media and popular culture. In parallel, scientists and educators try to find suitable instructional approaches to teach these topics in schools. A recent opinion piece in this journal argued for the need for more quantitative and formal approaches in GR education at the secondary school level. To provide a complementary perspective, I wish to make a case for the importance of qualitative and conceptual approaches, arguing that students benefit from opportunities to reason qualitatively. In doing so, I draw on my research and historical case studies to illustrate the importance of qualitative reasoning in GR. Discussions about the challenges and opportunities of different instructional approaches are meaningful because they help our community better understand why and how we should teach GR. As such, this opinion piece contributes to our joint efforts to improve the quality of general relativity education at the secondary school level and beyond.

Keywords: general relativity education; conceptual understanding; qualitative reasoning; physical intuition; Einsteinian physics

1 Introduction

The direct observation of gravitational waves has been called the discovery of the 21st century, "akin to Galileo's first turning of his telescope to the sky" (Grimberg et al., 2019, p.114). Fantastic progress in astrophysics has propelled us into an era where we can listen to the chirps of spacetime ripples and take pictures of the shadow cast by a black hole in the centre of our galaxy (Abbott et al., 2016; Akiyama et al., 2019). As these topics enter mainstream media and popular culture, the astronomy education research community has started to ask: "Should we teach general relativity in high school? Why and how?"

In a recent opinion piece of the same title, Horvath and Moraes (2021) addressed this important question – and rightly so! The physics of general relativity (GR) might be straightforward, but the most successful ways of teaching these topics are not obvious (Kersting and Steier, 2018). Since Horvath and Moraes outline routes to "carefully designed quantitative topics related to GR", arguing that "a hard science taught 'without mathematics' is not an achievement we should be proud of" (p. 51), I wish to provide a complementary perspective. More specifically, I wish to make a case for conceptual approaches in GR at the secondary school level, suggesting that we need to give students more, not less, opportunities to reason qualitatively. Doing so, I draw on my own research and historical case studies that illustrate the importance of qualitative reasoning in GR.

2 What is conceptual understanding anyway?

Being a mathematical physicist by training and having studied qualitative approaches to general relativity as part of my PhD in physics education (Kersting, 2019), I first wish to acknowledge where I fully agree with Horvath and Moraes: yes, we should teach GR in schools, not only to close the significant gap between frontier knowledge and educational practices but also to spark interest in physics and astronomy among our students and, in turn, society at large. And yes, mathematics is part of our logos, and the mathematical representation of physics is foundational. Few have expressed this fact so poetically as Eugene Wigner (Wigner, 1960, p.14):

> *The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve. We should be grateful for it and hope that it will remain valid in future research and that it will extend, for better or for worse, to our pleasure, even though perhaps also to our bafflement, to wide branches of learning.*

Having said this, I now explain why we as educators shouldn't underrate the importance of conceptual thinking in physics and astronomy – which is an occupational hazard for physicists who are wont to view mathematics as the language of science (Redish, 2005). Indeed, if some believe that "a qualitative, conceptual approach leads to the loss of a fundamental connection with other branches of science" (Horvath and Moraes, 2021, p.49), the crucial question for me becomes: what do we gain when developing students' ability to reason qualitatively in addition to solving equations?

Answering this question requires a better understanding of what constitutes conceptual approaches and qualitative reasoning in science, an explanation that goes well beyond the generic dichotomy of "hard science" and the "softening of physics and astronomy" (Horvath and Moraes, 2021, p.50). This dichotomy seems worn out and far too simplistic because it disregards the myriad ways scientists make meaning of the world. I believe that the very notion of "hard sciences" and an overemphasis on mathematics create false impressions of how physicists think and reason, which, in turn, can create obstacles to teaching physics. An instructional approach that tries to separate conceptual thinking from mathematical arguments does a disservice to GR education at all levels. After all, what is the benefit of having students who can do calculations without understanding what is going on physically - or why they do these calculations in the first place?

A short piece by David Sands (2014) provides an excellent starting point for obtaining a more nuanced view on conceptual understanding and qualitative reasoning in physics: "Concepts and conceptual understanding: What are we talking about?" Sands suggests that "the word 'conceptual' is commonly used to imply qualitative reasoning" (2014, p.7). He observes that "although this seems to involve the use of simple relationships, this kind of reasoning is actually far from simple".

3 Physics is more than just following mathematical logic

According to Sands, qualitative reasoning requires coordinating disparate areas of knowledge and invoking deep structural relationships between concepts. These are distinct processes that differ from quantitative reasoning based on mathematical treatments. Simple models, heuristic analogies, geometrical arguments, and visual relations all constitute examples of qualitative reasoning and are part of the conceptual toolbox that physicists use on a daily basis.

John Wheeler[1], who was very apt at approaching the relativistic study of gravitation geometrically and conceptually, echoes this observation when stating his "first moral principle" (Taylor and Wheeler, 1992, p.20):

> *"Never make a calculation until you know the answer. Make an estimate before every calculation, try a simple physical argument (symmetry! invariance! conservation!) before every derivation, guess the answer to every puzzle. Courage: no one else needs to know what the guess is. Therefore make it quickly, by instinct. A right guess reinforces the instinct. A wrong guess brings the refreshment of surprise. In either case, life as a spacetime expert, however long, is more fun."*

Turning further to the history of GR, we see that it was, in fact, not a qualitative, conceptual approach that led to a fundamental disconnect between GR and other branches of physics and astronomy. Instead, a key obstacle in making GR a working part of mainstream astronomy was the purely quantitative, i.e., mathematical, approach that prevailed until the 1950s. Bernard Schutz argues that "general relativity, despite its essential mathematical completeness in 1916, did not become a complete theory of physics until the 1970s" (Schutz, 2012, p.259).

Schutz observes that a crucial achievement of the generation of physicists who revived relativity, among them Wheeler, was the creation of a wide range of valuable concepts, "thereby adding the physics to the mathematical skeleton of the theory" (2012, p.260). According to Schutz, this process entailed connecting heuristic concepts using physical intuition – the same process that Sands identified as qualitative reasoning

4 A case for conceptual approaches in GR education in secondary schools

If we translate this insight to the teaching and learning of GR, we see why we should not disapprove of conceptual approaches so quickly. Just as qualitative reasoning practices were necessary to fruitfully further progress in relativistic gravitation, so are instructional approaches focusing on qualitative reasoning essential if we want to foster students' conceptual understanding and physical intuition in GR (Kersting et al., 2018).

Of course, this emphasis on the qualitative aspects of GR does not mean that we should neglect mathematical treatments altogether. Recent years have seen a growing body of instructional approaches in GR that draw on elementary mathematics and quantitative approximations (e.g. Czarnecka and Czarnecki, 2021; Gould, 2016; Hamilton and Lisle, 2008; Kersting et al., 2020; Kraus and Zahn, 2018; Lotze and Simionato, 2021; Pereira, 2021; Schutz, 2003; Uggerhøj et al., 2016).

However, I push for an educational agenda with a greater emphasis on conceptual understanding where we give secondary school students more, not less, opportunities to reason qualitatively in GR. There are at least two important reasons for choosing qualitative over quantitative approaches in GR.

First, it takes imaginative efforts to explore the physical implications of a mathematical theory that asks us to let go of absolute space and universal time (Kersting, 2020). Many learners experience relativistic phenomena as counterintuitive, often even in direct conflict with everyday experience and pre-existing knowledge (Kersting et al., 2018). Mere mathematical treatments can hardly help overcome the conceptual and "cognitive" conflicts students suffer in this learning domain (Velentzas and Halkia, 2013).

One key finding of my PhD research indicates that upper-secondary students can obtain a qualitative understanding of GR when provided with appropriately designed learning resources (Kersting et al., 2018). What is needed to support learners in their meaning-making of GR are instructional approaches that, among other things:

1. emphasise how GR relates to and sometimes breaks with classical physics (Figure 1).
2. link key concepts of GR to students' lifeworlds to counteract the lack of experience with relativistic phenomena.

1 Thanks to Markus Pössel for bringing this quote to my attention in a conversation.

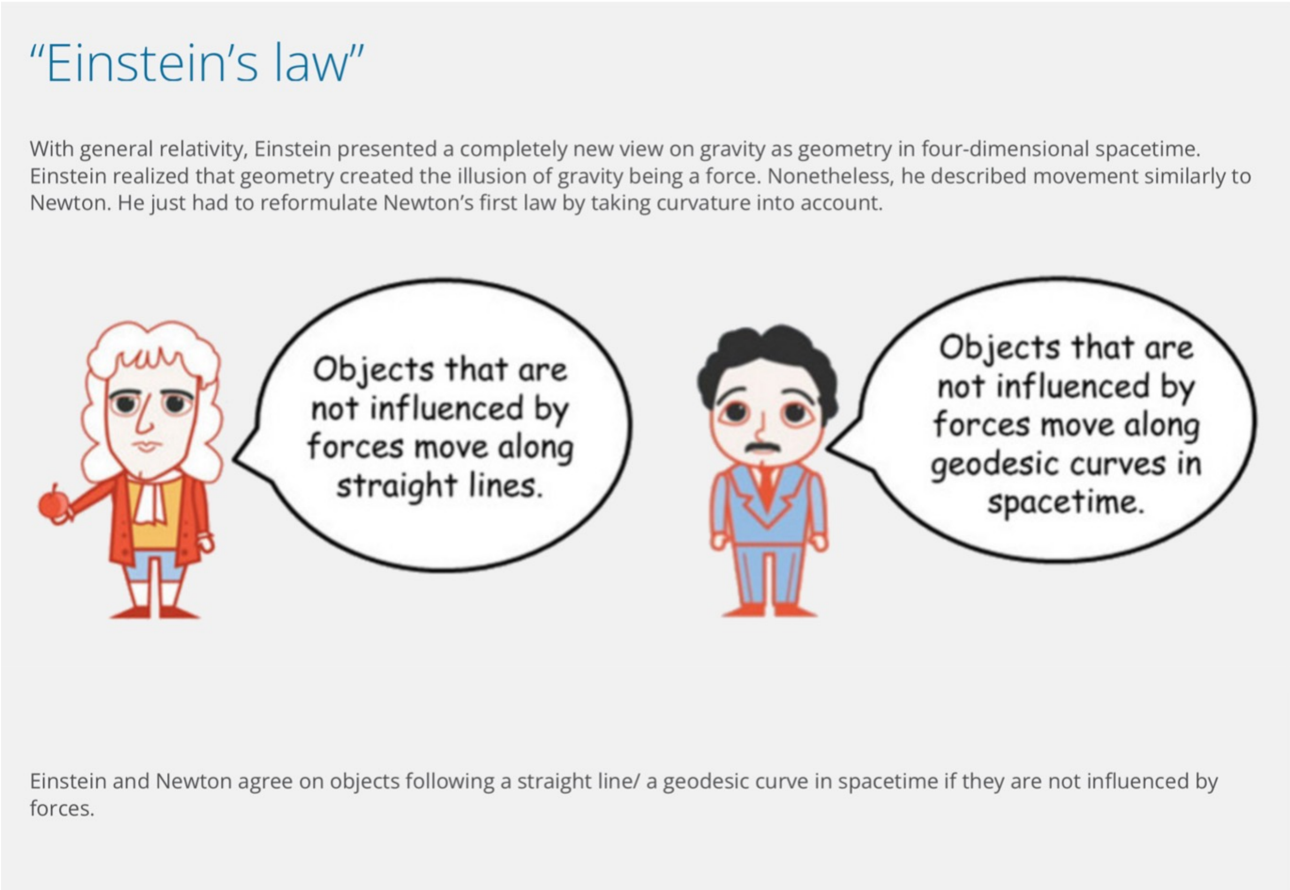


Figure 1. In the digital learning environment General Relativity, students learn how general relativity relates to and sometimes breaks with classical physics. In this screenshot, Newton's First Law of Motion is compared to Einstein's spacetime generalisation of this law: www.viten.no/relativity.

3. give students the opportunity to "talk physic"' with their peers by using discussion tasks that probe conceptual understanding of key concepts in GR (Figure 2).
4. explain that our qualitative understanding of GR can be made rigorous by employing advanced mathematics (Figure 3).

These design principles arose from an iterative process of developing and trialling learning resources for upper secondary school students in a four-year design-based research project (Kersting et al., 2018). We designed these resources with a particular view to fostering qualitative reasoning in GR. In particular, our research with secondary school students in Norway confirms what Schutz (2021, p.14) observes in a recent piece on the role of scientific intuition in Einsteinian physics:

> *Difficult subjects, like Einsteinian physics, can be introduced successfully using intuitive concepts (...) Many of these intuitions will link up with the ones that students already have, leading to a grasp of much of the physics even without elaborate mathematics.*

Second, conceptual approaches in physics education at the secondary school level can convey what it means to reason like a physicist and encourage an appreciation of the scientific enterprise. Of course, only a few students will grow up to become scientists, and even fewer will ever use the mathematics of relativity in their day-to-day activities. In fact, many secondary school students will possibly never take another science course again.

Nevertheless, all students can get a glimpse of what it means to think and talk like a physicist when engaging in qualitative reasoning exercises (Figure 4). All students can get an impression of how physics knowledge is created and how physicists rigorously and routinely challenge each other's ideas to advance the frontiers of our understanding (Figure 5). Conceptual approaches show that discussions and arguments matter just as much as equations if we want to make sense of the universe around us.

Not least, my research suggests that conceptual approaches may foster motivation and interest in physics and astronomy (Kersting et al., 2018, 2021). Paying attention to qualitative reasoning in GR can serve the more intangible purpose of exposing students to our current best understanding of the universe early, thereby stimulating a life-long love of science and possibly future careers in science. As Sean Carroll (2012) phrased it so aptly:

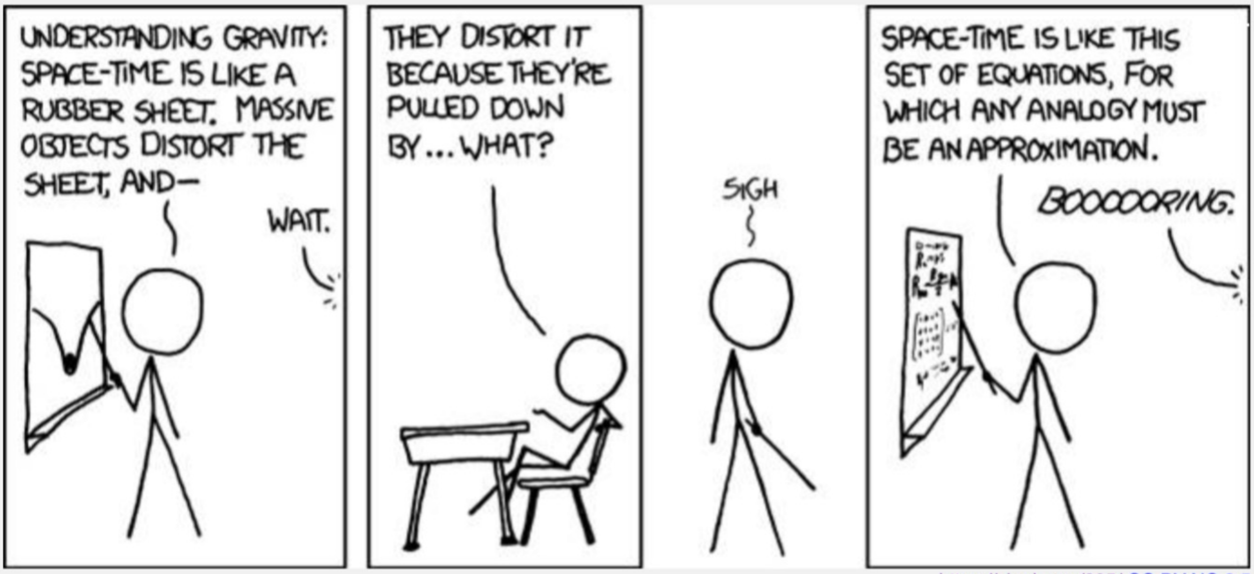
> *At heart, science is the quest for awesome - the literal awe that you feel when you understand something profound for the first time. It's a feeling we are all born with, although it often gets lost as we grow up and more mundane concerns take over our lives.*

5 So what?

It is often said that the conceptual and the technical are inseparable in advanced domains of physics. However, GR is one area where this separation is meaningfully possible (Bandyopadhyay and Kumar, 2010). Let us use this opportunity to make a case for conceptual approaches in physics and astronomy education. Such approaches help teachers bring one of the greatest discoveries of the 21st century into secondary physics classrooms. An increased focus on qualitative reasoning in GR allows students to engage in an essential part of what it means to think like a physicist and foster an interest and appreciation of physics and astronomy that goes far beyond the ability to do calculations.

Discuss the cartoon

Use your knowledge of general relativity to discuss the cartoon.



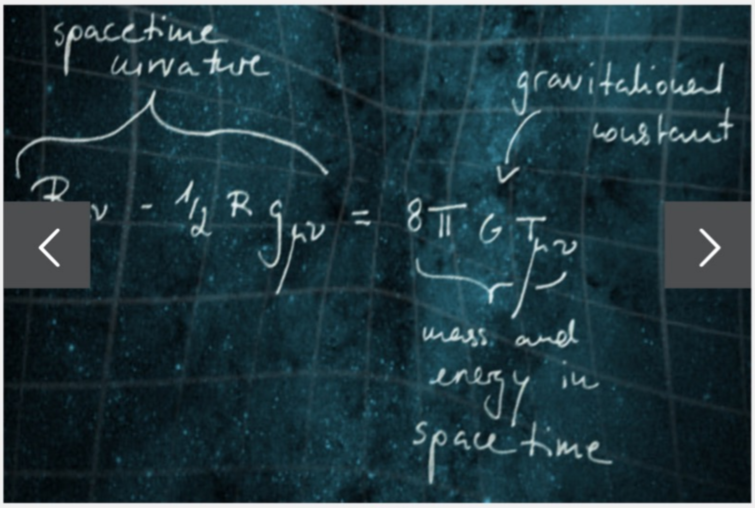
Writing task 4

Write a short summary of your discussion.

Figure 2. This exercise of the digital learning environment General Relativity invites students to use written and oral language to probe their conceptual understanding of abstract concepts: `www.viten.no/relativity`.

Mass curves spacetime

Gravity is a phenomenon connected with mass. Massive objects distort the geometry of spacetime by curving both space and time. It is difficult to visualize curvature in four dimensions, but we can use analogies in two and three dimensions.



Einstein's field equation

Even though it is difficult to visualize curvature in four dimensions, it is possible to calculate it. Einstein described gravity with an equation showing that the curvature of spacetime is proportional to the mass and energy present in spacetime. The constant of proportionality is Newton's classical gravitational constant.

Figure 3. The conceptual approach in the digital learning environment General Relativity acknowledges that our qualitative understanding of general relativity can be made rigorous by employing advanced mathematics: `www.viten.no/relativity`.

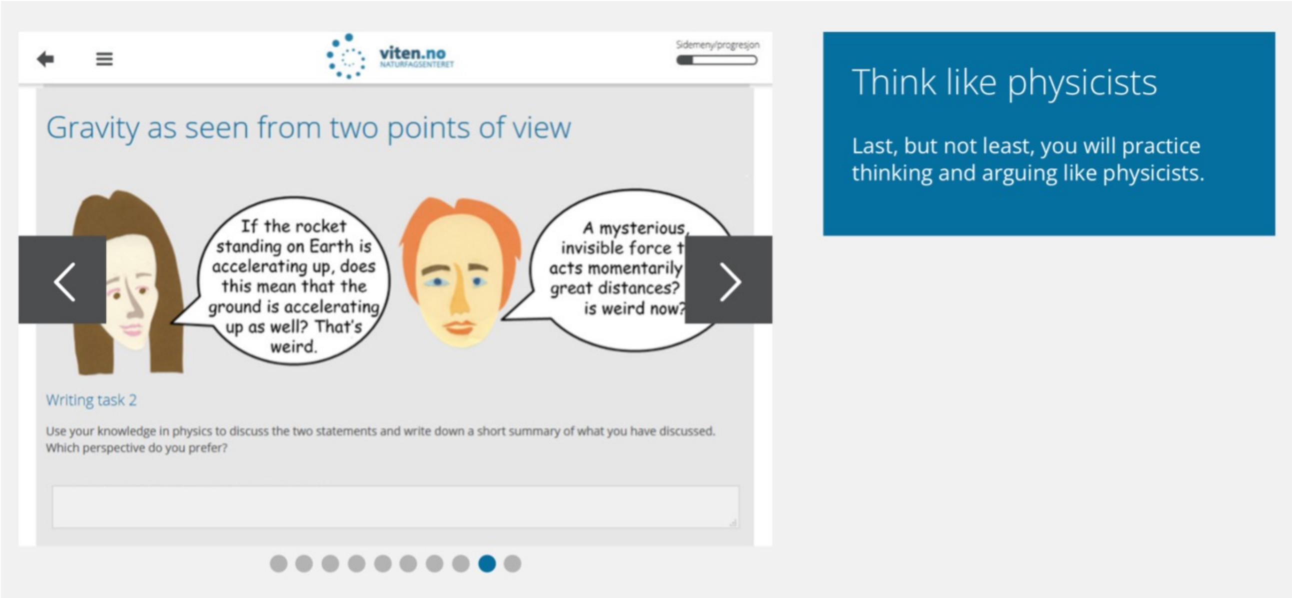


Figure 4. The digital learning environment General Relativity invites students to talk, argue, and think like a physicist and offers many discussion tasks with peers: `www.viten.no/relativity`.

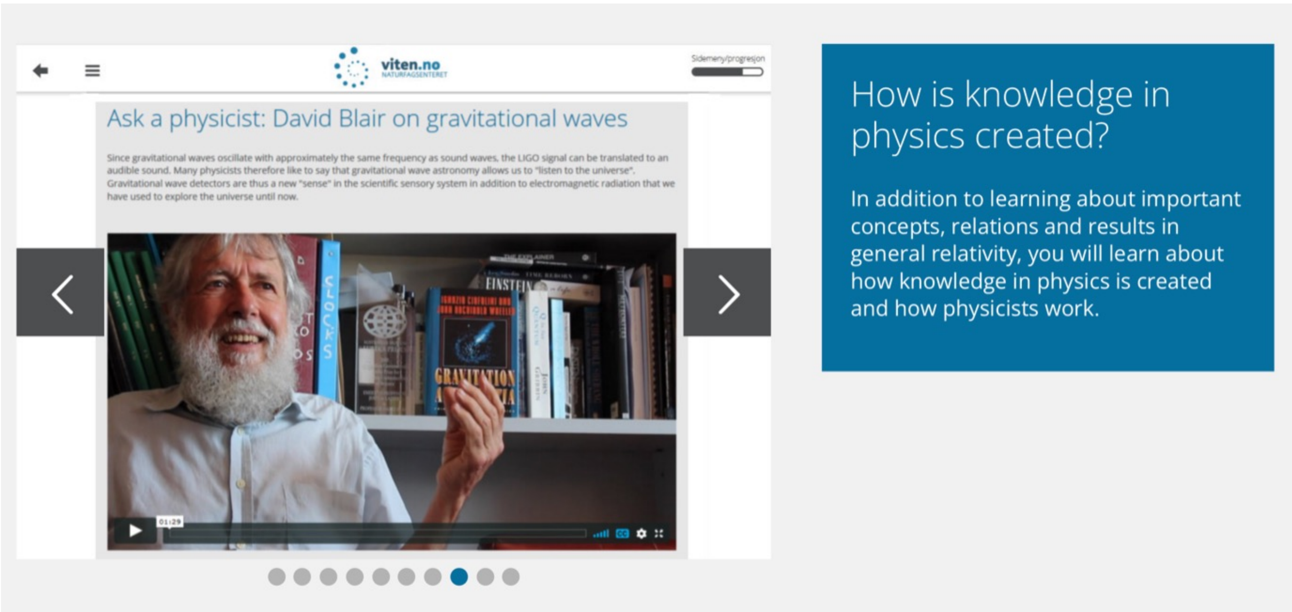


Figure 5. How do physicists work and how do they advance our knowledge of the world? The digital learning environment General Relativity employs conceptual approaches with a focus on the nature of science to help students answer these questions: `www.viten.no/relativity`.

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