Using the language of gravity to teach about space, time, and matter in general relativity

Magdalena Kersting

What?

This chapter explores the links between space, time, and matter in general relativity. Presenting three instructional models and two lesson plans, Magdalena Kersting suggests how the vocabulary of gravity can enrich teaching and learning of general relativity.

For whom?

Readers who look for instructional models and lesson plans to teach concepts of general relativity at the upper secondary school level.

Readers who wish to learn more about the pedagogical perspective of talking physics.

Introduction

For most people, the force of gravity is a ubiquitous background fact. We are so used to navigate a world governed by the laws of gravity that we take gravitational phenomena for granted. Yet, once we start thinking about these phenomena more carefully, the concept of gravity becomes remarkably elusive. Gravity, as a familiar phenomenon offers an instructional entryway to Einsteinian concepts of space, time, and matter while providing an example of how different scientific models can describe the same physical phenomena. There is a great need for authentic instructional approaches that introduce students to current scientific models to create awareness of the way scientific knowledge is produced, constantly re-examined, and further refined by scientists.

This chapter presents an opportunity to re-examine the ways gravity is taught in schools. Doing so, we explore the links between space, time, and matter and suggest three instructional approaches and two lesson plans that help secondary school students build conceptual understanding of gravity. By unpacking the surprising links between gravity, space, and time, the chapter places particular emphasis on the role of language in learning physics.

The presentation of this chapter follows a three-fold structure: First, we present a pedagogical perspective that emphasises the close link between language and physics. This perspective can help teachers and educators facilitate productive discussions when introducing Einsteinian conceptions of gravity in their classroom. To illustrate our pedagogical viewpoint, we present the vocabulary of gravity that physicists routinely use to describe gravitational phenomena. Second, we describe three instructional models that allow addressing the Einsteinian concepts of space and time through gravity. Third, we present two lesson plans that use the language of gravity and the three instructional models to introduce secondary school students to space, time, and matter in general relativity.

Pedagogical perspective: language and science

There is general agreement among science educators that the learning of science is both a scientific and a linguistic act (e.g. Bratkovich, 2018). Psychologist Lev Vygotsky (1962) proposed that the development of scientific concepts and the development of word meanings are the same process. According to this view, scientific thought comes into existence with the acquisition of scientific vocabulary. Indeed, some physics educators have gone so far as to claim that “the mastery of science is mainly a matter of learning how to talk science” (Lemke, 1990, p. 153). This linguistic perspective becomes especially relevant in Einsteinian physics because the advanced mathematical formalism of relativity and quantum physics is often inaccessible at the high school level. “Talking physics” is one successful instructional approach to address this challenge in the learning domain of Einsteinian physics (Bungum, Bøe, & Henriksen, 2018; Kersting, Henriksen, Bøe, & Angell, 2018).

Just as with learning a foreign language, fluency in physics requires practice at speaking, not just listening. Teachers can capitalise on that insight by inviting students to use written and oral language to promote conceptual understanding. Successful strategies to let students integrate Einsteinian concepts into their existing scientific vocabulary include the following (list adapted from Kersting et al., 2018):

1. Use open discussion tasks that probe conceptual understanding of Einsteinian physics concepts to give students the opportunity to reason with their peers.
2. Let students summarise their understanding of Einsteinian physics concepts in written exercises to let them practise the use of new physics vocabulary.
3. Use plenary discussions guided by the teacher to consolidate understanding and resolve misconceptions.
4. Raise awareness that some confusions and contradictions in physics discussions are not inherent to Einsteinian physics but rather a byproduct of the limited vocabulary that everyday language offers.
5. Emphasise that qualitative understanding of Einsteinian physics can be made rigorous by advanced mathematics.

The vocabulary of gravity

To make the pedagogical perspective of talking physics more tangible, we now take a look at three different vocabularies that physicists routinely employ to talk about gravity. Often, different ways of talking about gravity enable different intuitions of gravitational phenomenon (Chandler, 1994). Therefore, fluency in the vocabulary of gravity is beneficial in teaching and learning about space, time, and matter in general relativity.

Gravitational force

With the formulation of his three laws of mechanics, Newton described the motion of objects using the concepts of inertia and force. The vocabulary of forces is widespread in physics. A force is linked to the intuitive notion of pushing or pulling. The force of gravity is attractive and acts between massive objects, for example by pulling an apple down to the centre of the Earth. More precisely, a force is an interaction that leads to objects being accelerated. The gravitational acceleration of an apple (or any other object) in free fall is independent of the object; gravity is, therefore, universal. Mathematically, a force is a vector with a magnitude and direction that describes how much it will change the motion of an object.

Teaching students the vocabulary of forces and inertia has several pedagogical advantages. First, forces play a fundamental role in the way physicists describe the universe. An early introduction to the force concepts helps students become acquainted with classical mechanics and the mathematical formalism of vectors. Second, since students are familiar with the sensations of pushing and pulling, instructors can describe forces by appealing to students' intuitions of motion (Young, Freedman, Sandin, & Lewis Ford, 1999). In particular, the explanation that gravity pulls things downwards is appealing because it can be "fluently formulated in language, and [is] thus easily accessible to conscious elaboration, analysis, and reflection" (Kapon & DiSessa, 2012, p. 267). Third, Newtonian mechanics offers a coherent conceptual system that has the potential to impact students' learning similarly as it did impact scientists adopting the system in the first place (Hestenes, Wells, & Swackhamer, 1992).

However, physics education research has shown that the force concept presents students with conceptual challenges. Often, students' intuitions and their commonsense beliefs about motion are incompatible with Newtonian concepts (Hestenes et al., 1992). Many students leave physics instruction with misconceptions of forces. These misconceptions seem to exist independent of the instructor or the mode of instruction. Moreover, the force of gravity appears to act, somewhat mysteriously, at a distance. There is no apparent connection between the Earth and the Sun and the moon, no apparent mediator between these massive objects; yet, gravity holds them together in the solar system. From a pedagogical perspective, the force of gravity, thus, might appear counter-intuitive and for some even absurd or impossible (Chandler, 1994).

Gravitational field

The introduction of the notion of fields shifts the discussion of gravity to a higher level of abstraction. Fields are powerful conceptual tools in physics. Treating fields as physical entities that possess energy and momentum represents an important paradigm in modern physics (Feynman, 1970). A field is a physical entity that has a value for each point in spacetime, and that value can change with time. Although the most studied fields in physics are those that describe the fundamental forces, it is entirely possible to use the vocabulary of field theory without referring to the notion of forces. Thus, the field of gravity provides an alternative vocabulary to describe gravitational phenomena.

The link between the gravitational field and the gravitational force is via the gravitational potential energy. A physical object with mass has potential energy in relation to another massive object. It is this potential energy that we associate with the gravitational field. The force of gravity is the action of the gravitational field at a certain point in spacetime. By multiplying the gravitational field of an object at a specific location with the mass of a given test particle, you obtain the gravitational force that the object exerts on the test particle at that location. In other words, the gravitational force is the gradient of the gravitational potential energy field.

From a pedagogical perspective, the vocabulary of fields seems to be more abstract than that of forces. In contrast to forces, fields cannot easily be associated with pulls and pushes or with any other concrete physical entity. Chandler suggests that "perhaps as science becomes more advanced, its theories become increasingly counter-intuitive, and the more we learn about gravity, the less sense it will make" (1994, p. 165).

Yet, despite the higher level of abstraction, the vocabulary of fields has a broader scope than the notion of the gravitational force. For example, we can describe the fall of an apple off a tree via a potential well. The potential could, of course, represent the force of gravity, but it could also represent gravitational time distortion (Einstein, 1907).

Gravity and geometry

Einstein introduced the language of differential geometry to account for the universality of gravity. Based on the principle of equivalence and the insight that, locally, one cannot distinguish gravity from acceleration, Einstein linked the physics of gravity to the mathematics of geometry. Differential geometry describes spacetime as a mathematical structure that is locally flat, but that can be curved on a global scale - just like the Earth appears flat to us but is a curved sphere in reality.

While the human mind struggles to perceive four dimensions directly, the vocabulary of differential geometry allows physicists to work with the abstract concept of spacetime to make precise predictions about gravitational phenomena. Moreover, replacing Newton's mysterious force of gravity with a geometric mechanism, Einstein's vocabulary offers an explanation rather than a mere description of gravity.

However, the enormous explanatory power of differential geometry comes hand in hand with one great disadvantage, namely its inaccessibility at the high school level. The advanced mathematical formalism renders Einstein's vocabulary of gravity incomprehensible to many (Levrini, 2002). Even though many instructional models use students' geometric intuitions to present key ideas of general relativity, there remains the challenge of separating the mathematical formalism from the conceptual foundations of Einstein's theory of gravity.

Instructional models that link gravity, space, and time

In this section, we present three instructional models of gravity in line with an Einsteinian perspective. Each model capitalises on the close link between gravity, space, and time in a different way. Using the linguistic explorations of the previous sections as our backdrop, we unpack instructional opportunities and limitations of each model before presenting a comprehensive lesson plans in the next section.

Gravity and space – the rubber sheet model

The popular rubber sheet model visualises the dynamic interplay between spacetime and matter (Figure 1). The model compares spacetime to a stretched fabric; marbles or balls represent massive objects that curve the material which, in turn, changes the movement of the marbles on the sheet. Historically, the rubber sheet model has become a widely used instructional tool to make sense of four-dimensional curved spacetime. The use of malleable fabrics such as rubber and cloth to illustrate features of relativity reaches back to the very beginnings of the theory of relativity (Russell, 1925).

Linguistically, the rubber sheet model is appealing because it illustrates the catchy phrase "spacetime tells matter how to move, matter tells spacetime how to curve" (Wheeler, 1998). The model thereby relates Einstein's vocabulary of geometry to the vocabulary of forces and movement with which students are familiar. Moreover, its main elements "confirm so much to our expectations from everyday experience that the model can be presented as a narrative" (Pössel, 2018, p. 13). In comparing spacetime to a rubber sheet, the model establishes an analogical link between the rubber sheet (an everyday object students know well) and the abstract concept of spacetime. Based on the assumption that conceptual understanding of general relativity is linked to an active level of word knowledge, the rubber sheet model can serve both as a productive analogy and as a feature of relativistic thought that students develop to reason about gravity (Kersting & Steier, 2018).

<INSERT FIGURE 14.1 HERE>

Educational opportunities and limitations of the rubber sheet model

An instructional model works when it satisfies its purpose, namely conveying a key idea of an abstract scientific concept. Educators and physicists hold divided opinions on the educational value of the rubber sheet model (Kersting & Steier, 2018). Strengths of the rubber sheet model include the visual power, simplicity, and intuitive explanation of gravity that the model provides. The deformed sheet presents a mechanism of how gravity arises, and this analogy has great explanatory power: it is suitable to show orbital motions, curved space, and photon trajectories (Kersting & Steier, 2018). Besides, the rubber sheet is a dynamic continuum and is, therefore, a “welcome antidote to people whose mental picture of gravity includes a boundary for, say, the Earth’s gravity” (Pössel, 2018). Thus, the rubber sheet model can counteract the development of misconceptions related to the idea that there is no gravity on the moon or in outer space.

Yet, despite these educational opportunities, no instructional model comes without limitations (Kersting & Steier, 2018). Since the rubber sheet model depicts four-dimensional spacetime as a two-dimensional spatial sheet and suppresses the time dimension, the model emphasises the role of space over the role of time. This emphasis on spatial curvature is misleading; particularly so, because we experience gravity on Earth mostly because of warped time and not curved space (Kersting, 2019a). Besides, the rubber sheet model obscures the intrinsic nature of spacetime curvature. The universe does not curve into an “unseen dimension” like the two-dimensional rubber sheet that bends into the third dimension of space. Finally, the rubber sheet model makes use of gravity to explain gravity and, thus, obscures the physical mechanism of gravitational phenomena in general relativity.

Gravity and time – the ageing Earth model

By interpreting gravity as a manifestation of spacetime curvature, general relativity has a greater explanatory scope than Newtonian gravity. Still, on Earth, we mostly experience the laws of physics following the Newtonian theory. Physicists call gravitational conditions that reduce to this classical framework the "Newtonian limit". In this limit, particles move slowly compared to the speed of light, and the gravitational field is weak and not changing in time. Remarkably, in the Newtonian limit, gravity is an effect of warped time. Thus, in contrast to what the rubber sheet model suggests, our classical experience of gravity as the cause of planets orbiting the Sun and objects falling to the ground is due to temporal distortions of spacetime (Gould, 2016; Pössel, 2018).

Time dilation is one measurable effect of how gravity affects time. Depending on the gravitational potential and its gradient, time might pass more slowly or more quickly. In everyday life, the effects of time dilation are not noticeable. Still, there are ways to relate students' daily experience to this relativistic phenomenon. One such way goes back to Richard Feynman. Feynman observed that the centre of the Earth is younger than its surface due to gravitational time dilation. A hypothetical measurement of the age of the Sun or the Earth will yield different results depending on whether the measurement is performed at the surface or near the centre of the galactic object. This difference in age is “a fascinating demonstration of time dilation in relativity, and as such a very illustrative example for use in the classroom” (Uggerhøj, Mikkelsen, & Faye, 2016, p. 8).

When introducing the ageing Earth as an instructional model, teachers can use the vocabulary of the gravitational field to help students build an understanding of how gravity and time are closely interlinked. Gravitational time dilation might seem abstract and far away from students’ lived experiences. The ageing Earth model provides a concrete example of how the difference in the gravitational potential leads to time passing differently at the surface and the centre of the Earth. Moreover, the example of the ageing Earth allows a quantitative treatment of gravitational time dilation. Teachers can invite students to use mathematics as well as the vocabulary of fields to understand the link between time and gravity in general relativity (Uggerhøj et al., 2016).

<INSERT FIGURE 14.1 HERE>

Educational opportunities and limitations of the ageing Earth model

Gravitational time dilation is a minuscule effect when considered in everyday life. Thus, it can be challenging for students to relate to time dilation because the phenomenon seems counter-intuitive. While the ageing Earth model provides an example that presents a measurable time difference of several years, the challenge of relating to the scale of the effect remains. Students often struggle to understand long time scales such as the age of the Earth or cosmic distance scales such as the size of the Earth and other planets. Nonetheless, the ageing Earth model is pedagogically valuable because it presents a complete solution to the relativity of ageing due to differences in the gravitational field. Students can, therefore, practice the use of the field vocabulary in addition to becoming familiar with quantitative treatments of time dilation, as well.

Gravity and time - the warped-time model

Arguably, it is challenging to visualise temporal distortions. Thus, many instructional models of Einsteinian gravity do not take the time dimension into account. In the previous section, we have seen how one can link time and gravity by drawing on the phenomenon of time dilation. Here, we present an interactive warped-time model that illustrates a different approach to connecting time and gravity.

Physicists routinely use height-time diagrams to depict movement through space as a function of time. An interactive height-time diagram lies at the heart of the warped-time model that is freely accessible at the Norwegian learning platform Viten (Figure 3): www.viten.no/relativtiy

The warped-time model offers physics teachers an illustration of the fact that we experience gravity on Earth because of warped time (Kersting, 2019a). By drawing and discussing the trajectory of an object in free fall, students have the opportunity to explore the physics of gravity according to Newton and Einstein. In a traditional height-time diagram, the trajectory of a freely falling object corresponds to a parabola. Newton explains this trajectory as the result of the force of gravity accelerating an object down to the ground. To move from a Newtonian to an Einsteinian perspective, students warp the time-axis of the height-time diagram upwards by moving a slider. In this curved diagram, the parabola trajectory of a freely falling object gets stretched into a straight line. Instead of interpreting gravity as a force, Einstein understands gravity as a geometric phenomenon. An object in free fall follows the straightest possible path in a curved space. This observation is a generalisation of Newton's first law to the realms of four-dimensional curved spacetime.

<INSERT FIGURE 14.3 HERE>

Educational opportunities and limitations of the warped-time model

The warped-time model compares Einstein and Newton’s theories of gravity by using a representational tool that high school students are familiar with. Height-time diagrams allow students linking their previous knowledge of movement in a gravitational field to a relativistic model of gravity. Moreover, thought experiments are powerful tools to communicate relativistic concepts to high school students (Kersting et al., 2018; Velentzas & Halkia, 2013). Taking the physics of free fall as its starting point, the warped-time model makes use of one of Einstein’s most famous thought experiments that students can easily relate to.

However, just like the rubber sheet model, the warped-time model has inherent limitations because the model translates the physics of movement in four-dimensional spacetime to a two-dimensional visualisation. One limitation is the exaggerated warping of the time-axis: the mass of Earth is not big enough to warp time to an extent as presented in the simulation. Besides not being true to scale, the curved visualisation of the warped-time diagram is not a correct coordinate depiction either: a straight line in the diagram does not correspond to a straight line in spacetime. Rather than being geometrically precise, the model serves the pedagogical purpose of promoting a qualitative understanding of Einstein’s theory (Kersting, Toellner, Blair, & Burman, 2020).

Lesson plan: using the vocabulary of gravity to teach about space, time, and matter in general relativity

In this section, we present the lesson plan of one double lesson (90 minutes) that introduces secondary school students to concepts of space, time, and matter in general relativity. A second lesson plan can be downloaded in the e-resources. Both lessons invite students to "talk physics" and to practice using the vocabulary of gravity in discussion and writing tasks. Lesson 1 is an introductory lesson that encourages students to explore the links between gravity, curved space, and warped time through qualitative reasoning and discussions with peers based on the rubber sheet and the warped-time model. Lesson 2 is a more advanced lesson that builds on concepts developed in lesson 1 to guide students to a deeper understanding of gravitational time dilation using the ageing Earth model and elementary calculations. Table 1 gives a brief overview of how the content of the two lessons links to common topics of physics curricula.

<INSERT TABLE 14.1 HERE>

Lesson 1 – Linking gravity to the geometry of curved space and warped time

In this introductory lesson of 90 minutes, you engage your students in qualitative thinking processes that lead to an exploration of geometry as the cause of gravitational phenomena. The lesson aims to foster qualitative understanding of the four-dimensional nature of spacetime by inviting students to talk physics. Working in pairs or small groups, students follow an instructional sequence from the digital learning environment *General Relativity* that is freely accessible at www.viten.no/relativity.

Learning goals

After completing this lesson, students will be able to

- use the vocabulary of forces to describe Newton’s model of gravity
- use the vocabulary of curved space and warped time to describe Einstein’s model of gravity
    - describe general relativity as a theory relating space, time, and gravity
    - describe the universe as having three spatial dimensions and one time dimension
    - explain how gravity can be interpreted as a geometric phenomenon
    - describe how mass curves spacetime and how the curvature of spacetime influences the movement of mass
- compare Newton and Einstein’s model of gravity and conclude that general relativity has a greater explanatory scope

Instructional models and approaches

In this lesson, students will work with the **rubber sheet** and the **warped-time model** in the digital learning environment *General Relativity*. Open discussion tasks, writing tasks, and plenary discussions challenge students to practice the **vocabulary of the gravitational force and geometry** in the context of general relativity.

In pairs or small groups, students work through parts of modules 1 (The Principle of Equivalence) and 3 (Curved Spacetime) at their own pace. Alternatively, you can pace the flow of the lesson by guiding your students through each part of the module, making sure to allow for enough time for group and plenary discussions.

Optional additions to the lesson include a hands-on activity with a physical rubber sheet model or a discussion of gravitational bending of light (as outlined in the second part of the module "Curved Spacetime" at www.viten.no/relativity).

Instructional sequence (90 minutes)

The instructional sequence follows parts of the presentation in modules 1 (The Principle of Equivalence) and 3 (Curved Spacetime) of the digital learning environment *General Relativity*. In Table 2, we provide an overview of the instructional steps.

<INSERT TABLE 14.2 HERE>

Conclusion

The familiar phenomenon of gravity offers different instructional entryways to Einsteinian concepts of space, time, and matter. In this chapter, we have used the vocabulary of gravity to present three instructional models that link gravitational phenomena to curved space and warped time. While the rubber sheet model illustrates gravity as a manifestation of curved space, the ageing Earth model and the warped-time model invite students to explore the links between gravity and time. By offering teachers several instructional models, all of which are complimentary and capitalise on different vocabularies of gravity, this chapter promotes a contemporary way of teaching gravity. First, the pedagogical emphasis on language fosters conceptual understanding and qualitative reasoning in a learning domain that often has a reputation of being inaccessible to younger learners. Second, the two lesson plans provide examples of how different scientific models can describe the same physical phenomena. The lesson plans, therefore, offer opportunities to introduce students to the nature of science and raise awareness of the way scientists continuously produce and re-examine scientific knowledge. Despite its ubiquitous presence, gravity has eluded human understanding for centuries and has challenged some of the keenest minds in the history of science. It is by emphasising this historical struggle and by illustrating the links between space, time, and matter that students can obtain a comprehensive picture of gravity in line with our current best understanding of the universe.

Further reading:

E-resources: Lesson 2 – Exploring how the gravitational potential influences the rate at which time passes

Chapter 10: Models and analogies in teaching general relativity

Chapter 19: Designing learning resources and investigating student learning in general relativity and quantum physics in Norway

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