Students’ understanding of gravity using the rubber sheet analogy: an Italian experience

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Abstract
General relativity (GR) represents the most recent theory of gravity, on which all modern astrophysics is based, including some of the most astonishing results of physics research. Nevertheless, its study is limited to university courses, while being ignored at high-school level. To introduce GR in high school, one of the approaches that can be used is the so-called rubber sheet analogy (RSA), i.e. comparing space-time to a rubber sheet that deforms under a weight. In this paper, we analyse the efficacy of an activity for high-school students held at the Department of Mathematics and Physics of Roma Tre University that adopts the RSA to address several topics related to gravity. We present the results of the questionnaires we administered to over 150 Italian high-school students to investigate their understanding of the topics treated.

Keywords: gravity, einstein, general relativity, space-time, secondary education, hands-on activity, experimental activity

1. Introduction
The most recent and successful theory describing gravity is the theory of general relativity (GR), introduced by Albert Einstein in 1916 [1]. This theory relies on the concept of space-time, a four-dimensional entity that unifies space (which has three dimensions) and time (one dimension). According to this theory, the space-time changes according to the objects placed in it: a massive object (a galaxy, a star, a planet, a dog) deforms the space-time producing gravity, i.e. attracting nearby masses.

All modern astrophysics, including some of the most important and recent discoveries of the field [2–5], is based on GR. However, its study is typically addressed only in advanced university courses, while it is ignored at lower levels of education, such as in high schools, where gravity is only described using the Newtonian theory.

The reasons for this are many. The mathematical complexity of GR forces us to adopt a purely qualitative approach, which is not easy to realise without oversimplifying the concepts too much. Moreover, even if one decides to only deal with
the basic concepts at a qualitative level, such as the space-time and its deformation, he/she will have to accept a new vision of the world, far from the everyday experience.

In recent years, several efforts have been made in order to address these issues and create activities suitable to introduce GR in school curricula [6–16]. Several other works focus on the quantitative analysis of students’ understanding of gravity and GR, ranging from very young children to university students [17–30]. This present paper aims at contributing to this discussion through the analysis of questionnaires administered to over 150 Italian high-school students who participated in an activity we designed to teach gravity and GR.

The model we used is the popular rubber sheet analogy (RSA), which compares the space-time to a rubber sheet that deforms under the weight of a mass, and allows gravitational attraction to be simulated through marbles and balls thrown onto the warped sheet. Although this model shows some critical points extensively addressed in the literature [13, 31–33], it represents a powerful activity [6, 11, 18, 34] that has already been demonstrated to be much welcomed by Italian high-school teachers [35].

For this reason, at the Department of Mathematics and Physics of Roma Tre University, we built a structure that could support a lycra sheet, and we used it in the RSA to realise an activity addressed at high-school students that could deal with different topics such as Kepler’s laws, gravity assist, gravitational lensing and black holes. We asked all participants to answer three questionnaires: one before the activity, one immediately after and one four months later. In this way, we investigated their understanding of the most important aspects addressed during the activity, and the possible presence and persistence of misconceptions or wrong beliefs.

The remaining paper is organised as follows. In section 2 we briefly describe the structure we used to exploit the RSA, the activity and the corresponding questionnaires. In section 3 we illustrate the results of our research, focussing on the main aspects that are revealed. In section 4, we discuss our achievements and in section 5 we present our conclusion and suggest some future development of our work.

2. Background and data collection

In order to carry out an activity that dealt with gravity using the RSA we built a circular structure 1.8 m in diameter of aluminium covered by a lycra sheet of about 2 × 1.5 m (figure 1), in collaboration with the mechanical shop of the INFN Roma Tre section. We chose this size for the structure to ensure that a group of about 25 people (a typical Italian high-school class) could comfortably watch what was shown on the sheet.

In the period of January–February 2020 we used this structure to carry out our activity with six high-school classes, engaging more than 150 students. Before, after and four months after the activity, we asked the participants to answer three questionnaires in order to explore their understanding of the topics addressed.

2.1. Description of the activity

The activity consists of a lesson lasting an hour and a half during which moments of strong interaction with participants using the rubber sheet are alternated with theoretical insights using videos and photos. We start with a description of the model of RSA: we first introduce the concept of

Figure 1. The 1.8 m diameter structure of space-time we built at the Department of Mathematics and Physics of Roma Tre University in collaboration with the mechanical shop of the INFN Roma Tre section.

3 The answers to our questionnaires were anonymous. This study was carried out in accordance with the principles outlined in IOP Science ethical policy.
space-time and how it is related to gravity, using a central weight and some marbles; we then focus on the simplifications that the usage of the rubber sheet implies, that can lead to misconceptions and wrong beliefs. We believe that bringing these misconceptions to light helps participants to overcome them (an idea that has been confirmed by the results of the questionnaires, as we will see in the following). First of all, we underline that space-time can be deformed by any mass (or energy) and not only by big masses. Then, we clarify that the rubber sheet represents a two-dimensional space-time. We thus point out that the space-time curvature originated by a spherical object is symmetrical in all directions, and therefore that there is no privileged direction in the Universe, contrary to what both the rubber sheet and our daily experience on Earth could lead us to think. In other words, there is not an up and down, but only a near or far from the source of gravity.

After these first clarifications, we start to show the participants how this model, although simplified, can allow us to visualise quite faithfully the way in which planets orbit the Sun, i.e. following Kepler’s laws. Once the basic rules of the game are shown, we show other examples of motion of celestial objects. We show the Earth–Moon system, the orbits of a planet around two stars and the phenomenon of gravity assist, which can explain the typical voyage of a space probe. It is worth reminding that throughout these activities the students are actively involved, and experience first-hand the behaviour of the marbles when throwing them on the sheet: in this way their attention is kept high, and they become more willing to ask questions and join in with the discussion.

At this point, we provide a fairly complete picture of how the space-time and its deformation describe the phenomena that the students have only studied in terms of Newtonian gravity. Then we focus on the topics fully explained only by GR. We start with the phenomenon of gravitational lensing, representing light with a marble that deflects its trajectory when approaching the central weight. Through videos and photos, we then show the participants the consequences of this phenomenon, and how it is used by astrophysicists to characterise celestial objects. We then introduce black holes, explain that they are compact objects, underline the fact that they strongly affect only the surrounding region and restate that this attraction does not point downwards. Finally we talk about the gravitational waves, the way in which scientists have discovered them and their usefulness in improving our knowledge of the Universe.

2.2. Description of the questionnaires

We use three questionnaires: one administered before the activity in order to analyse the prior knowledge of the participants, one administered right after the activity so that we could investigate the knowledge acquired thanks to the activity, and one questionnaire administered four months after the activity in order to study the permanence of the knowledge obtained.

All the questionnaires have the same structure: a first part that deals with the age and the school attended by the participants, a second part that focusses on the Newtonian theory of gravity and a third part that considers more complex topics related to GR.

When designing the answers to the questionnaires we paid attention to adding distractors so that we could investigate the presence of wrong beliefs and misconceptions.

While the two questionnaires administered after the activity are identical, between the questionnaires administered before and after there is a slight difference: the pre-questionnaire includes both multiple-choice questions with five alternatives (one of which was always ‘I do not know’) and open questions, while the post-questionnaires only used multiple-choice questions with five alternatives, one of which could eventually be an open answer.

3. Results

Overall we obtained 153 answers to the questionnaire administered just before the activity, 125 answers to the one administered just after the activity and only 42 to the one administered four months after the activity. This relevant decrease in the sample is mainly due to the fact that, unlike the other two, the last questionnaire was administered remotely, and in the period when Italian schools were closed due to the first Covid-19 lockdown;
Newtonian gravity is typically introduced during the third year, the majority of the participants already have knowledge of it. The percentage for each answer is shown in brackets (left: pre-questionnaire, right: post-questionnaire).

Figure 3. The distribution of the answers to the question What is the space-time? The percentage for each answer is shown in the legend in brackets (left: pre-questionnaire, right: post-questionnaire).

3.1. What is space-time and how it is deformed?

To assess the participants’ understanding of the concept of space-time and its deformation, we asked for a definition of space-time (figure 3). Before the activity, 46% of the students’ answers were correct (It’s the union of space and time, which together form a four-dimensional entity), while 34% of them stated that it was two-dimensional. The remaining 20% of the participants confused space-time with the fourth dimension, or with speed (which in schools is usually defined as the ratio between space and time), or said they did not know. After the activity, the percentage of correct answers increased: over 90% of the participants stated that space-time had four dimensions, while only 6% still confused the concept of space-time with the fourth dimension. After four months this positive trend was confirmed, since the percentage of correct answers was 86% (see the appendix).

We then focussed on the cause of the deformation (figure 4). Before the activity with the rubber sheet, the majority of respondents (58%) said that they did not know if anything could deform space-time, while 1% stated that nothing could deform it and 41% declared that it could be deformed.
Among the latter, 9% generically stated that it could be deformed, 28% gave a correct example of a source of deformation, and 4% gave a wrong example.

Immediately after the activity, 60% of the participants stated that the cause of deformation could be any mass, 34% referred to a large mass, while 3% cited a force that points downward. The same trend could be found four months after the activity, when the answer ‘big mass’ was cited by 31% of the participants (see the appendix).

3.2. Kepler’s laws and gravity assist

Later, we investigated the participants’ knowledge of Kepler’s three laws.

Before the activity, the majority of the students already remembered Kepler’s first law, since 90% stated that the orbit shape that a planet takes around the Sun is elliptical (figure 5). Four percent said that planets have a random orbit, while less than 1% admitted they did not know. Immediately after the activity, the situation slightly improved, since the percentage of correct answers stayed high (95%), while the remaining 5% of participants gave wrong answers. Even after four months, 93% of the sample gave the correct answer (see the appendix).

Kepler’s second law shows a more considerable improvement (figure 6). Before the activity, in fact, just over half (52%) of the participants correctly answered when asked about the way in which planets move around the Sun. The others (48%) thought that the planets moved slower when they were closer to the Sun (16%), that they always kept the same speed along the orbit (16%), and that they were faster both when they approach the Sun and when they move away from it (15%). Right after the activity the percentage of correct answers rose to 83%, while all the other wrong answers reduced. Four months after the activity about 80% of the sample of respondents still remembered the correct answer (see appendix).

Regarding Kepler’s third law, participants were asked which planets orbit faster around the Sun (figure 7). Before the activity, 70% already
If we want to reach Saturn with a probe, it is better to make it do:  

| Option | Pre-questionnaire | Post-questionnaire |
|--------|-------------------|--------------------|
| Some orbits around one or more planets, so that we can exploit the gravity assist (40% - 75%) | 32% | 45% |
| Some orbits around one or more planets, so that we can exploit the gravitational lensing (70% - 14%) | 6% | 7% |
| We orbit around the Earth and then a straight line to Saturn (5% - 4%) | 10% | 14% |
| A straight line to Saturn (8% - 1%) | 2% | 4% |
| I don’t know / None of the previous answers (2% - >1%) | 1% | 0% |

The percentage for each answer is shown in the legend in brackets (left: pre-questionnaire, right: post-questionnaire).

Figure 8. Distribution of answers to the question If we want to reach Saturn with a probe, it is better to make it do: The percentage for each answer is shown in the legend in brackets (left: pre-questionnaire, right: post-questionnaire).

3.3. Gravitational lensing, waves and black holes

Before the activity, less than half of the participants (44%) gave the right answer when asked to describe the phenomenon of gravitational lensing (figure 9), while 41% declared they did not know at all. The remaining 16% confused the phenomenon with something related to a glass lens, or explained the phenomenon using the Italian word ‘lens’ (= ‘lenti’, meaning ‘slow’ instead of lens). After the activity, the correct answers rose to 93%, while the percentage of those who associated the phenomenon with a glass lens remained unchanged (3%). Also, after four months, the percentage of correct answers confirmed an improvement of the result (98% of correct answers).

Regarding gravitational waves, before the activity, about 52% gave the correct definition of them (figure 10). The remaining half was made up of 21% who admitted they did not know what they were, and 27% who gave wrong answers, confusing them with other topics they had studied in school (waves formed on water) or with concepts they had heard about after the discovery of gravitational waves (such as black holes and lasers). After the activity, 83% gave the correct definition. After four months we had 81% correct answers.

Finally, we asked the participants to give us a definition of black holes (figure 11). Before the activity, 57% did not feel confident enough to give an answer. Less than 2% gave completely wrong answers (the escape speed, nitrogen, a place where there is emptiness). The remaining 41% gave an answer not far from the correct one: 24% associated black holes with a mass, a body...
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Figure 11. Distribution of answers to the question What is a black hole? The percentage for each answer is shown in the legend in brackets (left: pre-questionnaire, right: post-questionnaire).

or a dead star, 9% with a deformation of space-time, 3% with something that absorbs everything, or nearby matter, or energy or light, and 5% associated them with a very intense gravity or with something that cannot be escaped. After the activity, the percentage of correct answers rose to 79%, given that they associated black holes with something that attracts only nearby matter. Only 7% chose the answer inserted as a distractor, i.e. that the black hole attracts matter downward. This was also confirmed by the trend shown in the answers four months later: 84% gave the right answer, while only 7% recalled the idea of an object that was attracted downward.

4. Discussion

Overall, the students who participated in our activity with the rubber sheet significantly improved their knowledge of the topics addressed. This trend was also confirmed by the responses obtained four months after the activity.

As regards the topics usually treated in school, the activity straightens their knowledge and improves their understanding. The most significant case in this sense is Kepler’s second law, which the rubber sheet has helped to visualise and remember. In particular, while the first law was already known before the activity by the majority of students (90%), the second was remembered only by the 52%. This trend could suggest that the second law is studied in school in a more mnemonic way with respect to the first law, without sufficient understanding. In fact, if we consider only the students attending the third year (who had just covered Kepler’s laws in school, and thus should remember them better), we note that only 62% of them correctly recalled the second law before the activity, while the first law reaches a percentage of 95% (figure 12).

Moreover, when verbally asked during the activity, the participants often remembered the statement of the second law ‘A line segment joining a planet and the Sun sweeps out equal areas during equal intervals of time’ but they evidently did not understand its meaning. Only when they saw the motion of the marbles on the sheet did they really understand it, as confirmed by the results of the post-questionnaires. In fact, after the activity, the percentage of correct answers for the second law also became very high, as shown in figure 13 (86%).

Regarding the topics that are not typically treated in school, like black holes, gravitational waves and gravitational lenses, the data show a prior knowledge lower than that related to Kepler’s laws, as might be expected.

Despite this fact, also for these topics the improvement was remarkable, since the percentage of correct answers increased from less than a half of the total to almost 100%. Our analysis also shows that the acquired knowledge seems to be lasting, given that almost all of the respondents of our sub-sample continued to correctly answer even four months after the activity. Moreover, it
can be seen that, although these topics are not addressed in high-school curricula, they were not completely unknown by the students even before the activity. This could be a sign of a widespread fascination for these topics, which encourages the students to search for information even if they are not taught in school (as indicated by the fact that they gave reasonable answers even before the activity: black holes are ‘dead stars’, ‘space-time deformations’, ‘somewhere you cannot escape from’), or at least of a strong bond with current news (as suggested by the answers we received for the gravitational waves, related to lasers or black holes).

Our analysis also suggests that the rubber sheet can also be effective in dealing with the misconceptions and wrong beliefs related to gravity. In particular, our data allowed us to investigate two misconceptions: the fact that the deformation of space-time is only due to large masses and the idea that gravity is always a force that points downward. As regards the former, the data show that our activity, even having faced this aspect, does not solve it completely, since a substantial percentage of students (34%) after the activity refer only to very big masses when asked about the source of deformation. This means that greater attention must be paid in fighting this idea throughout the activity with the rubber sheet, emphasising more than once that space-time is not only related to stars and galaxies, but also to objects with smaller mass, such as those that populate our everyday life.

Regarding the idea of a gravity that points downward, our data show that it can indeed be fought using the RSA, since only 3% of our sample chose the distractor (‘a force that points downward’) when asked to specify what deforms space-time. This means that the discussion made at the beginning of the activity, which deals with the absence of a privileged direction of gravity outside the Earth, and with the limitations of the RSA, paid off. Our idea is also confirmed by the results obtained four months after the activity, when the answer ‘downward’ completely disappears, and also by the results obtained regarding black holes.

Overall, our analysis therefore leads us to think that the rubber sheet, albeit with all its limitations, represents a formidable tool for introducing GR at high-school level, given that it helps students both to visualise how gravity works and to remember it for longer.

5. Summary and conclusion

In this paper we presented the results of the questionnaires we administered to over 150 high-school students who participated in the activity held at the Department of Mathematics and Physics of Roma Tre University that used the RSA to address several topics related to gravity. Our data show that the rubber sheet can indeed be very useful not only in teaching topics that can be explained by GR, but also to better understand and remember the topics generally addressed in high school using the Newtonian theory of gravity.

In the near future we plan to continue to test our proposal, involving an increasing number of students. In particular, we hope to resume the activity in person, so that we could also follow more closely the compiling of the questionnaire administered four months after the activity, in order to have statistics comparable to those obtained with the questionnaires distributed right before and right after the activity. This will help us to better understand and quantify the long-term effect of introducing the rubber sheet at high-school level.
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Figure A1. The results of the questionnaire administrated four months after the activity.
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