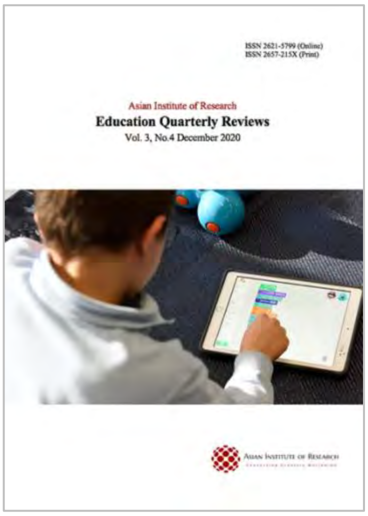

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Probing High School Students' Understanding of Einstein's Theory of Gravity Using Thought Experiments and Analogy

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Abstract
In this study, we probed high school students' understanding of Einstein's theory of gravity by implementing an approach which mainly consists of two steps: firstly, exposing students to TEs describing the Equivalence Principle; secondly, applying the analogy of parallel lines on a curved surface with the path of two falling balls in a real gravitational field to help students deduce the idea of gravity as the spacetime curvature. A total of 12 high school students voluntarily participated in this study where data regarding their understanding were measured by means of an identical pen-and-paper test and interviews. Even though none of the students could explain what the Einstein's version of gravity is in the pre-test, their responses in the post-test indicated that the approach we applied could help them understand the Einstein's theory of gravity. Not only could they recall what the gravity is, most of them managed to provide related analogy they have learnt to explain their thoughts. Apart from its easily comprehensible steps, the study suggested that the approach is worth adopting to teach Einstein's theory of gravity as it reflects the similar path ever taken by Einstein when starting to formulate his theory of gravity.

Keywords: Einstein's Theory of Gravity, Thought Experiments, Analogy, Students' Understanding

1. INTRODUCTION

Efforts to bring general relativity related concepts, such as Einstein's theory of gravity, gravitational deflection of light, black holes, and gravitational waves to high school students have increasingly been conducted for the last few years. Among others, pilot and follow up programs conducted by collaborating researchers in *the international Einsteinian Physics Education Research* (*EPER*) are worth mentioning. In recent years, this international collaboration which comprises researchers in Australia (Einstein-First Project), Norway (Project ReleQuant), and Germany (The Spacetime-Travel Project) has been actively developing and testing appropriate learning materials and approaches used to teach Einsteinian physics to high school students (Choudhary, Kraus, Kersting, Blair, Zahn, & Zadnik, 2019).

Researchers in the Einstein-First Project developed and tested learning resources, mainly consisting of spacetime simulator (rubber sheet model), tungsten balls and marbles, woks, and toy cars to teach general relativity related concepts (Foppoli, Choudhary, Blair, Kaur, Moschilla, & Zadnik, 2018; Kaur T., Blair, Moschilla, Stannard, &

Zadnik, 2017; Pitts, Venville, Blair, & Zadnik, 2013). In the Spacetime-Travel Project, Zahn and Krauss developed sector models to teach curved spacetime, gravity and black holes (Kraus & Zahn, 2019; Zahn & Kraus, 2014; Zahn & Kraus, 2018). In the ReleQuant project, digital and research-based resources were developed to teach general relativity theory (Kersting & Steier, 2018; Kersting, Bøe, Henriksen, & Angell, 2018; Kersting, 2019). Despite the difference in methods and approaches used, these researchers seem to agree that concepts related to general relativity are better delivered to high school students by using models and analogies (Kaur, et al., 2018; Kersting & Steier, 2018; Zahn & Kraus, 2014).

In addition to the use of models and analogies, thought experiments (TEs) have also been used as an assisting tool to teach and explain theories of relativity (special and general theory of relativity). Velentzas & Halkia (2013), for instance, used "Einstein's elevator and Einstein's train" TEs to teach basic concepts of relativity. Their study indicated that TEs can help students understand abstract concepts such as the equivalence principle, the relativity of simultaneity, time dilation, and length contraction. The use of TEs is also found in several well-known books popularizing Einstein's theories of relativity, such as *Black Holes & Time Warps: Einstein's Outrageous Legacy* (Thorne, 1994), *Gravity from the ground up* (Schutz, 2003), *Spacetime Physics: Introduction to Special Relativity,* and *Exploring Black Holes: Introduction to General Relativity* (Taylor & Wheeler, 1991, 2000). In the context of teaching the Einstein's theory of gravity, Kersting (2019) emphasized the importance of introducing and capitalizing TEs before using warped time model to teach Einstein's theory of gravity.

The use of models, analogies and TEs to teach Einstein's theories of relativity is arguably reasonable considering the highly abstract nature of the theories. In fact, theories of relativity are sourced from Einstein's brilliance of using his genuine TEs to overturn classical idea about the interrelationship of space, time, and matter. Therefore, using TEs in teaching and learning Einstein's theories of relativity is reasonably beneficial to helping students visualize abstract concepts in their minds and develop their imagination (Galili, 2009), triggering their interests about the topics being discussed (Velentzas, Halkia, & Skordoulis, 2007) and more importantly, raising their awareness about the importance of the long and natural connection of TEs to the development of the theories (Stinner & Metz, 2006). Equally important is the use of models and analogies to explain Einstein's theories of relativity. As theories of relativity, in particular the general theory of relativity is formulated in abstract and complicated mathematics formula, models and analogies have been used in order to make concepts related to theories accessible in more simplified ways. The use of models and analogies is hoped to facilitate understanding of abstract concepts as the process allows students to analogize the similarities between objects or events in their world and the phenomena under discussion (Treagust & Duit, 2012). Moreover, the use of models and analogies is expected to help students construct mental models of abstract phenomena by referring to their existing or previous experience in order to interpret more complex ideas (Silva, 2006).

In the context of the theory of gravity, Einstein proposed a new feature of gravity which is very distinct from the old Newtonian gravity. Newton defines gravity as a force emanating from massive objects while according to Einstein gravity is a manifestation of curved spacetime (Einstein, 2005). Arguably, Newton explains gravity using a more familiar concept: a force. Einstein, on the other hand, has adopted a more abstract concept to explain gravity: the curvature of spacetime. In fact, spacetime itself is an abstract concept; it is a four-dimensional entity which we cannot directly perceive as we live in a three-dimensional world. Hence, apart from its mathematics complexity, it is quite obvious that even to explain Einstein's theory of gravity conceptually, we do need models and analogies.

One of the most frequently used models to explain Einstein's theory of gravity is the elastic rubber sheet model or pillow model or sometimes called spacetime simulator model (Baldy, 2007; Dua, Blair, Kaur, & Choudhary, 2020; Kaur T., Blair, Moschilla, Stannard, & Zadnik, 2017). In this model, spacetime is mimicked by the elastic rubber sheet and to represent the idea of spacetime curvature, a massive object like a heavy tungsten ball is put on that elastic rubber sheet to make it curved. Smaller objects put on that curved elastic rubber sheet will perform any movements depending on the sheet distortion. Using this model, one can reproduce Einstein's theory of gravity as encapsulated in John Wheeler's words, "*matter tells spacetime how to curve; curved spacetime tells matter how to move*" (Wheeler, 1990). Without the presence of any massive objects, the stretched rubber sheet will remain undisturbed and this is considered to represent a flat spacetime which is an arena for the special theory of relativity.

This model is considered to have great explanatory power (Kersting, 2019) and the concepts mapped from Einstein's theory of gravity to this model is straightforward (Pössel, 2018).

Apart from positive points this model can offer, the model is mainly criticized due to the double role played by gravity which potentially leads to a conceptual confusion (Pössel, 2018; Price, 2016). The model uses gravity to explain gravity. The model uses Earth's gravity acting on a massive object to explain gravity which is represented by the curved space on the rubber sheet caused by that same massive object. This circular argument may lead to students' confusion (Janis, 2018). Besides that, this model can lead to a misunderstanding that gravity is a manifestation of curved space, not curved spacetime (Janis, 2018) as the model emphasizes the role of distorted space and obscures the role of distorted time (Pössel, 2018). To address the limitations of this model, alternative models and approaches have been suggested, such as the warped time model (Kersting, 2019), sector models (Zahn & Kraus, 2014, 2018) and the use of the concept of geodesic using analogies with paths of flying aircraft on the surface of the Earth (Janis, 2018; Stannard, Blair, Zadnik, & Kaur, 2016)

The present research

In order to minimize the emergence of alternative conceptions resulted from the use of previous models, this research was designedly aimed at probing students' understanding of Einstein's gravity by adopting a new approach which mainly consists of two steps: first, exposing students to TEs describing *the Equivalence Principle*; second, applying the analogy of parallel lines on a curved surface with the path of two falling balls in a real gravitational field to help students deduce the idea of gravity as the spacetime curvature.

While in the previous research students were directly told about what Einstein's gravity is and the use of models and analogies was to visualize the concepts (Dua, Blair, Kaur, & Choudhary, 2020; Kaur T., Blair, Moschilla, Stannard, & Zadnik, 2017; Pitts, Venville, Blair, & Zadnik, 2013), in this research, we encouraged students to perform TEs and use analogies to deduce Einstein's idea of gravity. In this case, we followed the similar path taken by Einstein himself when formulated his theory of gravity (Pössel, 2005; Thorne, 1994). We fundamentally believe that this approach can hinder students from taking for granted the idea of gravity as a manifestation of spacetime curvature.

a. *TEs describing the Equivalence Principle*

The equivalence principle is a fundamental principle in the theory of general relativity, which states that observations made in a uniformly accelerating reference frame ($\vec{a}$) are indistinguishable from observations made in a Newtonian gravitational field ($\vec{g}$), where $\vec{g} = -\vec{a}$. Expressed in Robert Dicke's words, "the (strong) equivalence principle might be defined as the assumption that in a freely falling, non-rotating laboratory the local laws of physics take on some standard form, including a standard numerical content, independent of the position of the laboratory in space and time. It is of course implicit in this statement that the effects of gradients in the gravitational field strength are negligibly small, i.e., tidal interaction effects are negligible" (Nobili, et al., 2013).

Several TEs have been designed to explain the equivalence principle. In this study, students were asked to perform two TEs. The first TE was about Einstein's happiest thought: "*if a person falls freely, he will not feel his own weight*". "The person will not feel his weight" means that locally (in his immediate vicinity), the person who is experiencing free fall in a gravitational field does not feel gravity. Why is that? The fundamental reason behind this is that *locally* this person is experiencing *a homogenous gravitational field*.

The TE designed to perform this Einstein's happiest thought is as follow:
Students were asked to imagine a freely falling person who is recording the motion of a ball thrown horizontally from a certain height and describe what the ball's path looks like as observed by this freely falling observer. Besides that, they were also asked to compare what the path looks like as observed by an observer standing on the ground.

The second TE was designed to describe the equivalence of gravity and acceleration. The TE is as follow:
Imagine a person who is in a windowless elevator located in a very deep space, free from gravitational influence of any gravitating masses. The person is holding two balls side by side and is about to release them. According to the person in the elevator, when the balls are released, what would happen to the balls when the elevator is at rest and when the elevator is accelerated at 9.8 m/s^2? Suppose that the balls fall to the floor, what would happen to the horizontal separation between the balls?

The first TE was designed to show that in a homogenous gravitational field, a person freely falling will detect no gravity. In this TE, freely falling observer is observing the ball moving in a straight line as if the ball were moving in a free gravity universe. The absence of gravity felt by the observer implies that the observer and moving ball are in a flat spacetime where the special theory of relativity holds. The expected responses to the situations described in the second TE are as follow: when the elevator is at rest, the balls released will remain floating at their initial positions. When the elevator is accelerated at 9.8 m/s^2, the person in the elevator will find that the balls fall and hit the floor as if they were dropped on the Earth's surface.

How about the horizontal separation between the balls? While in many textbooks, this second TE is commonly used to merely explain the equivalent effect caused by gravity and acceleration, in this study, however, we concentrated on the different feature of this TE. We used this TE to set the stage for students' mental realization about the difference of the effects caused by 'relative gravity' (Pössel, 2005) or pseudo gravity and the real gravitational field or intrinsic gravity.

In this study, we used the horizontal separation between two falling balls as a pivotal entry point to distinguish the pseudo gravity and the real gravity, which eventually leads to an understanding of gravity as a spacetime curvature. In an accelerated elevator, a person in that elevator will observe that the two balls fall to the floor as if they were being influenced by a real gravity. This kind of gravity is called relative gravity or pseudo gravity, characterized by its magnitude and direction homogeneity and reference frame dependence. To be precise, 'a gravitational field' caused by a constantly accelerated frame of reference is always a homogenous gravitational field. In this homogenous gravitational field, two freely falling balls *will not 'feel their own weights' (they are unable to detect the presence of gravity)* which implies that *they are moving in a flat spacetime*. Regarding their horizontal separation, the two balls are falling side by side in a homogenous 'gravitational field' and hence *their horizontal separation remains unchanged*.

In the real gravitational field, this is not the case. The Earth's gravity, for instance, is not uniform as the gravitational acceleration varies both in magnitude and direction. Regarding the horizontal separation of two balls falling in a real gravitational field, the inhomogeneity of the real gravitational field has the impact on changing their horizontal separation. The two balls initially falling side by side will have a tendency to fall on radial lines towards the Earth's center of gravity. Their paths can be depicted as follow*: the balls initially move parallel side by side. Due to the non-uniformity of Earth's gravity or sometimes called the tidal effect* (Pössel, 2005; Schutz, 2003; Thorne, 1994)*, after a certain period of time on their way towards the Earth, the balls will approach each other and their horizontal separation decreases.* Logically, in a real gravitational field, the balls must not move in a flat spacetime otherwise they will keep their horizontal separation as they do in the homogenous gravitational field.

b. *the analogy of parallel lines on a curved surface with the path of two falling balls in a real gravitational field*

In a Euclidean geometry, two parallel lines never meet; they are equi-distant. For instance, two parallel lines on a flat surface of a paper sheet never meet. On the curved space, in contrast, two parallel lines behave differently. On a curved surface, for instance, two lines which are locally parallel could meet at one point. The lines of longitude from the equator to the poles on the classroom globe are a good example.

In this study, students were asked to analyze the behavior of parallel limes on a flat and on a curved surface and compare it analogously with the behavior of two balls falling side by side in a homogenous gravitational field and in a real gravitational field. The nature of two parallel lines on a flat surface is analogous to the path of two balls falling side by side in a relative/homogeneous gravitational field. In this homogeneous gravitational field, the two balls detect no gravity and hence their spacetime is considered to be a flat spacetime. The flat surface is analogous to the flat spacetime. The fact that two balls falling side by side in a real gravitational field cannot keep their horizontal separation is analogous to what exhibited by two parallel lines on a curved surface. The curved surface is analogous to the curved spacetime.

c. *Payoff of the Analogy*

In a two dimensional curved space, it is the curvature of the surface that forces two lines, initially parallel, to shrink their separation distance and even cross at one point. In the case of two balls falling side by side in a real gravitational field, it is gravity (or to be precise: tidal effect of gravity) that causes the decrease of their horizontal separation distance. The effect caused by gravity on the falling balls is similar to what the surface curvature does on parallel lines. As the surface curvature is analogues to spacetime curvature, the gravity is, in conclusion, a manifestation of this spacetime curvature.

2. METHODS

1. Context of the research

This study was conducted in Sikka regency, East Nusa Tenggara province, Indonesi where a total of 12 (denoted as S1 to S12) grade XI majoring science students voluntarily participated in this study. The study was implemented in a five meetings program. In the first meeting, we administered the pretest and presented the concept of *spacetime* as a result of Einstein's postulate about the universality of the speed of light. In the second meeting, we highlighted *Newton's law of gravity* to remind students about what they had learnt in grade X and revealed *its limitations*. These limitations were not part of materials they had learnt in the Indonesia grade X physics curriculum. The core contents of this study were presented in the third and fourth meetings of the program. In the third meeting, students learnt about *the equivalence principle* and *Einstein's theory of gravity* was presented in the fourth meeting. A week later, the post-test was administered (fifth meeting).

2. Data Collection and Analysis

Data regarding students' understanding were measured by means of an identical pen-and-paper test administered before (pre-test) and after the five meetings program (post-test) and interviews. This open-ended test which consisted of six questions was designed to reflect our approach and to probe students' understanding of the Einstein's theory of gravity accordingly.

The first two questions were designed to probe students' understanding of TEs describing the equivalence principle (q_1 and q_2). The next two questions (q_3 and q_4) were to probe their understanding of the nature of two balls falling in a real gravitational field (q_3) and the behavior of parallel lines on a flat and curved surface (q_4). Q_5 instructed students to analogize the behavior of parallel lines on a flat and curved surface (q_4) with the paths of motion presented in q_3. In q_6, students were instructed to deduce Einstein's theory of gravity based on their answers to q_1 to q_5.

Students' responses as evidenced in their written answers were then analyzed. The analysis was focused on students' initial and final understanding about the concepts.

3. RESULTS AND DISCUSSION

Analysis of Students' Responses to the Questionnaire

1. Pre-test responses

A. *Students' responses to q_1 and q_2 about TEs describing the Equivalence Principle*

The q_1 was designed to probe students' understanding of the so-called *Einstein's Happiest Thought*: *if a person falls freely, he will not feel his own weight*. The question is as follow:
Imagine two persons, A and B, who are at a certain height above the Earth's surface. The person A throws a ball in a horizontal direction and at the same time, the person B makes a free fall (motion without initial velocity),

a) What is the shape of the ball's trajectory observed by the person B?
b) What is the shape of the ball's trajectory observed by a person C who is at rest on the ground?

The expected response to the q_1 is the person B observes a straight line trajectory while the person C observes a parabolic (downward curved) trajectory. The trajectory observed by the person C is what we commonly experience in our daily lives. The straight-line trajectory viewed by the person B can be explained as follow: a person in a free fall (person B) could not detect gravity and the ball, according to this observer, is also moving in a free gravity region where it travels in a straight line path.

The results indicated that the shape of the trajectory observed by the person C was quite obvious that most of the students gave the correct answer (10 out of 12). On the other hand, students seemed to perform a serious thought experiment to analyze the shape of the trajectory observed by the person B. Several responses that arose regarding the shape of the trajectory observed by the person B were: straight line/horizontal trajectory (S2, S3, S7, S9 and S13), curved trajectory (S10), upward curved trajectory (S8), tilted trajectory (S6), and that the ball doesn't have a fixed trajectory (S4). Three students gave unexpected responses such as "according to the person B, the ball initially moves in a horizontal line and then falls vertically to the ground" (S5); "the person B observes the ball moving faster" (S11), and "according to the person B, the ball is accelerated" (S1).

The fact that there were five students who managed to give the correct response indicated that the TE could actually be grasped by students. However, when confirmed by interviews about how they came up with their answers, three students just answered the question intuitively (not quite sure about the reason); S3 mentioned that "the observer and the ball fall down together and their position remains the same. Therefore, the observer sees the ball moving in a straight line"; S7 said "Straight line. I remember, if a ball is thrown horizontally and another ball is released vertically, both will hit the ground at the same time. So, [the situation is] like this [S7 explained by using his hands showing how two balls fall down together]. I think the case is similar to the problem given"

The q_2 was about the TE describing the equivalence of gravity and acceleration. Students were asked to answer the following question:
Imagine a person who is in an elevator located in the outer space (the person and the elevator are completely free from the effects of gravity). While in the elevator, the person is holding two balls, 1 and 2, as shown in the picture.

a) According to the person in the elevator, in which direction will the balls move when they are released in the elevator which is at rest?
b) According to the person in the elevator, in which direction will the balls move when they are released in the elevator which is accelerating upward with a certain acceleration? How is their separation distance?
c) If the elevator is accelerating at 9.8 m/s^2 upward (the acceleration experienced by an object when it falls on the Earth's surface), explain your ideas about the motion of the balls as observed by the person in the elevator! How is their separation distance?

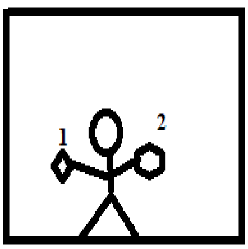

Figure 1: An observer in the lift

Regarding the q_2 (a), the majority of students responded as what expected that *the balls will float or remain at their places when they are released*. There were two students who gave different responses. S5 wrote: "the balls will fall down" and according to S9 "the balls will each other collide". Students' responses to the q_2(b) could be divided into three categories: first, when the lift is accelerated, the balls fall down in parallel lines (S1, S6, S8); the balls fall down and their separation distance is always the same (S3, S4, S7, S9). Second, when the lift is accelerated, the balls will remain floating (S2, S10, and S11). Third, the balls float into the air (S5); the balls move upward and hit the ceiling of the lift (S12). Regarding the q_2(c), in terms of the direction in which the balls will move, students' responses were consistent with their previous responses (q_2.b). Yet, none of the students pointed out the expected answer *that the two balls will fall to the floor as if they were being influenced by the real gravity*. The closest response was given by S8 who wrote "the balls will fall like objects falling from a certain height [on Earth]". S3 and S9 seemed to misinterpret the problem when they considered the existence of gravity. "Because there is a gravitational force, the two balls fall quickly in parallel lines" (S3); "There will be a gravitational force and two balls fall down in a straight line" (S9). Confirmed in the interviews, their assumption about the existence of gravity is due to the misinterpretation of the data regarding gravitational acceleration (9.8 m/s^2) mentioned in the problem. We were also interested in responses given by S2 who consistently responded that the balls will float (q_2.a) and will remain floating (q_2.b and q_2.c). In the interview, S2 explained as follow: "I think the balls float because there is no gravity. Even though the lift is moving, the balls remain floating". It is quite obvious that in this case the S2 positioned himself as an external observer, not as an in the lift observer.

B. *Students' responses to the path of two balls falling in a real gravitational field(q_3)*

The q_3 was about understanding the tidal force effect on changing the separation distance between two balls falling side by side in a real gravitational field. Students' understanding was gauged by the following question: Look at the picture!

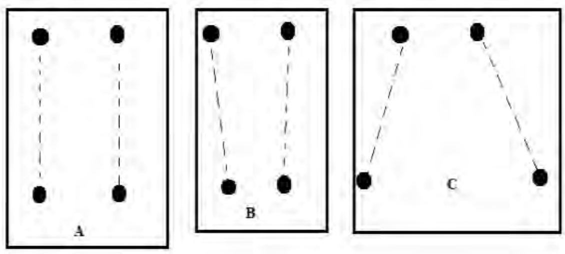

Figure 2. Two balls falling side by side in a real gravitational field

Two balls, originally put at a certain height, were dropped freely onto the Earth. After traveling a considerable distance for a long time, which picture do you think best describes the paths of motion of the balls? Explain why you chose that picture!

Responding to this question, 8 of 11 students (S1, S3, S4, S5, S7, S8, S9, and S11) chose the picture B, which was the expected answer. Yet, their reasons for choosing the option were unsatisfied. S1 and S11 proposed that it is the Earth's gravity that causes the balls to get closer. However, when confirmed in the interview, they both were unable to explain in more detail how the gravity affects the separation distance of the balls. S3 and S8 mentioned the influence of the wind velocity while the remaining four students simply reasoned (rewrote what mentioned in the problem) that the balls get closer due to a considerable distance the balls have travelled. Basically, we assumed that students who have learnt Newtonian gravity should have argued that objects falling in a real gravitational field (the Earth's gravity) will have a tendency to fall on radial lines towards the Earth's center of gravity, which is responsible for the shrink of their separation distance.

C. *Students' responses to the behavior of parallel lines on a flat and curved surface (q_4)*

In this research, we analogized the behavior of parallel lines on a curved surface with the paths of balls in q_3 in order to deduce Einstein's theory of gravity. Therefore, it is very crucial for students to have a compact understanding about the nature of parallel lines when located on a flat and curved surface.

The q_4 asked students to analyze whether two parallel lines on a flat or curved surface could meet.

Is it possible for two parallel lines to meet when

a) located on a flat surface?
b) located on a curved surface?

In the context of Indonesia, students have been familiar with the concept that two parallel lines will never meet. They have learnt this concept since they were in elementary schools. Some high school students even took this concept for granted and failed to recognize that the concept is only valid when the space is flat (Dua, Blair, Kaur, & Choudhary, 2020). However, in this research, students' pre-test responses revealed a surprising result. The majority of students (83.33%) believed that two parallel lines can meet when located in a curved surface. Nonotheles, two students had different ideas. S5 gave unclear response to this question. "On a flat surface, two straight lines are moving in one direction. On a curved surface, they are in opposite direction" (S5). It was S10 who still believed that " they [parallel lines] will never meet whatever the surfaces are".

D. *Students' responses to the analogy of parallel lines with the paths of the falling balls (q_5)*

The q_5 instructed students to analogize the behavior of parallel lines on a flat and on a curved surface (q_4) with the paths of the balls in q_3.

Analogize the condition of two parallel lines on a flat and curved surface with the paths of motion of the two balls in pictures A, B, and C in Q_3 above!

Responding to this question, all students agreed that two parallel lines on a flat surface were analogous to the paths of the balls in figure A in q_3. However, in the case of making the analogy of parallel lines on a curved surface with the path of the balls, S1 and S7 claimed that they were analogous with figure B; S4 and S11 mentioned that they were analogous with figure C; the remaining seven students (including S10 who believed that the lines never meet) analogized them with figure B and C; and S5 didn't give his opinion.

E. *Students' responses to what the gravity is*

"What do you know about gravity? Explain using analogies! (q_6)". As suspected, the majority of students understood gravity as an attraction force. "The gravity is an attraction force between two objects or masses"(S1, S2, S6, S12). "Gravity is the Earth's attraction force (S10, S11)"; Gravity is the force from Earth that attracts objects to its center" (S3, S9); Gravity is owned by planets such as the Earth. Gravity causes the free fall (S8). S7 didn't define what the gravity is but made a statement that "objects will float when there is no gravity". S4 and S5 defined gravity somewhat incorrectly that "gravity is a free fall force to the Earth's surface" (S_5); and "gravity is the attraction force between one atom with other atom" (S_4).

2. Post-test responses

A. *Students' responses to q_1 and q_2 about TEs describing the Equivalence Principle*

Responding to the $q_{1\,(a\,\&\,b)}$, all students agreed that the person B observes the ball to be moving in a straight line trajectory while the person C who is staying at rest on the ground sees a curved/parabolic trajectory. Regarding the $q_{2(a)}$, all students believed that according to an observer in the lift, the two balls will remain on their places or floating when they are released. Responding to the $q_{2(b)}$, most of the students gave a standard answer that the two balls will fall down and their separation distance does not change/remains constant. Several students provided additional information to their answers. "According to the person in the lift, the balls fall down and their separation distance is always constant. Yet, people on earth see the balls remain at rest when the lift is moving upward" (S1). "The balls fall not because there is gravity but because the lift is accelerating upward" (S3). "The balls fall due to [lift's] acceleration, not because of gravity" (S10). Regarding the $q_{2(c)}$, most of the students responded as expected that the balls fall with acceleration like on the Earth (S1, S4, S6, S9, S10, S12); the balls experience free fall like objects fall on the Earth (S2, S3, S8, S11). However, there were two students (S5 and S7) who simply mentioned that "the balls fall down".

B. ***Students' responses to the path of two balls falling in a real gravitational field(q_3)***

Responding to the q_3, 11 of 12 students chose the picture B (except S6 who chose the picture C) as the best picture which describes the paths of two balls falling side by side in a real gravitational field. Students choosing the picture B suggested the Earth's gravity as the main factor which causes the balls to approach each other. Several interesting answers are cited below: they approach each other because the Earth's gravity attracts them to fall towards the Earth's center (S7, S11); the balls falling in a real gravitational field will get closer, not like the balls falling in the lift (S9) [The student refers to the $q_{2(b)}$]; the balls approach each other because they are moving in an inconstant gravity [inhomogeneous gravitational field] (S3, S12), the balls approach each other because they are moving in gravity that changes with height (S10). We do expect students to mention "the tidal force" effect in their responses. However, none of them did. We interviewed S3 and S9 for why not mentioning "the tidal force effect" in their responses and they both confirmed that they simply didn't remember the terminology.

C. ***Students' responses to the behavior of parallel lines on a flat and curved surface (q_4)***

Regarding the behavior of parallel lines on a flat and curved surface, all students believed that on the flat surface, two parallel lines never meet. On a curved surface, they do. The result was not quite surprising as the majority of students had responded correctly to this question in the pre-test.

D. ***Students' responses to the analogy of parallel lines with the paths of the falling balls (q_5)***

As in the pre-test, all students responded that two parallel lines on a flat surface are analogous with the paths of the balls in the figure A (q_3). 10 of 12 students considered the parallel lines on a curved surface to be analogous with the balls' paths in the figure B in q_3 and only two students who argued that parallel lines on a curved surface are analogous to the figure B and C in the q_3.

E. ***Students' responses to what the gravity is***

Students' responses to what the gravity is can be grouped into three categories. The first category is students who directly wrote that gravity is a manifestation of spacetime curvature (S11) or a manifestation of spacetime which is curved (S5) without providing any additional information. Secondly, students who correctly defined gravity as a manifestation of curved spacetime and provided a simple analogy to explain what they meant (S1, S2, S3, S6, S8, and S12). "Gravity is a manifestation of spacetime curvature. Gravity causes the balls falling towards the earth to approach each other like two parallel lines on the curved surface" (S1). "Gravity is a manifestation of curved spacetime. It attracts the balls to the Earth's center which is the same as curved surface makes the parallel lines to meet in q_4" (S8). Thirdly, students who managed to present the complete analogy and deduce the idea of what the Einstein's gravity is (S4, S7, S9, and S10). "According to Einstein, gravity is not a force. It is a manifestation of curved spacetime. We can analogize spacetime with a curved surface. The curved surface causes the parallel lines to meet. The gravity causes the [separation] distance of two balls [falling in a gravitational field] decreases" (S4). "According to Newton, gravity is an attraction force. According to Einstein, gravity is a manifestation of curved spacetime. In q_3, two balls approach each other (figure B) which are the same as parallel lines on a curved surface. The curved surface is analogues to curved spacetime. It can be concluded that gravity is a manifestation of curved spacetime (S10).

Even though none of the students could explain what the Einstein's version of gravity is (q_6) in the pre-test, students' responses to q_1 to q_5 indicate a promising result about the approach we used. Their responses reveal that TEs and analogy we are using can be well grasped. Their pre-test responses also show that we can actually adopt familiar phenomena in Newtonian physics as 'infrastructures' to build an understanding of Einstein's gravity.

In the post-test, the results presented in this research indicated that the approach we applied could help students understand the Einstein's theory of gravity. Not only could they recall what the gravity is, most of them managed to provide related analogies they had learnt to explain their thoughts. It is arguably because the approach provides students with easily understandable steps to deduce the Einstein's theory of gravity. Apart from the fact that it is easily comprehensible, this study suggests that the approach is worth adopting to teach Einstein's theory of gravity as this approach reflects the similar path ever taken by Einstein when reformulating Newton's gravity.

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