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The equivalence principle comes to school—falling objects and other middle school investigations

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Abstract


Comparing two objects falling together is a small-scale version of Galileo's classical experiment, demonstrating the equivalence between gravitational and inertial mass. We present here investigations by a group of ten-year-olds, who used iPads to record the drops. The movie recordings were essential in the follow-up discussions, enabling the students to compare the different situations and to discern situations where air resistance was essential and where it could be neglected. By considering a number of familiar situations and simple investigations that can be performed, e.g., on a playground, students may come closer to an appreciation of the deep significance of the non-influence of mass on motion under gravity.

1. Introduction

The equivalence between inertial mass (in ma) and gravitational mass (in mg) is a powerful principle with remarkable, counterintuitive consequences. It makes a hammer and feather fall together in vacuum—or on the Moon [1]. It is the reason astronauts are weightless and that the pendulum's frequency is independent of its mass. It makes it possible for amusement parks to offer the experience of 'zero g ' in free fall drop towers or parabolic parts of roller coaster rides. It is also the basis for the concept 'g-factor' or 'g force' used to describe, e.g., the experience of

feeling heavy at the lowest point of a playground swing, in roller coaster turns or during a spacecraft launch. The term 'equivalence principle' was coined by Einstein, as part of his work to extend the special theory of relativity, leading him to the conclusion that acceleration and gravity cannot be distinguished [2]. The equivalence principle has been tested in a number of precision experiments that search for small deviations depending on the materials or particles involved [3, 4], including searches for possible differences between matter and antimatter⁵. These are all 'null experiments', which establish ever lower limits for possible effects.

A consequence of the equivalence principle can be easily demonstrated in a classroom, by letting, e.g., two balls of different mass fall together

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⁵ See, e.g., home.web.cern.ch/topics/antimatter.

from a moderate height, as a miniature version of Galileo's legendary demonstration:

But I, Simplicio, who have made the test can assure you that a cannon ball weighing one or two hundred pounds, or even more, will not reach the ground by as much as a span ahead of a musket ball weighing only half a pound, provided both are dropped from a height of 200 cubits [5].

Demonstrations were, in fact, performed more than a millennium before Galileo [3], but were forgotten. For Newton, there was no longer a question: 'It has been, now for a long time, observed by others, that all sorts of heavy bodies (allowance being made for the inequality of retardation which they suffer from a small power of resistance in the air) descend to Earth from equal heights in equal times', and he observed that this equality of descent marked off gravity from all other forces [3].

Still, the equivalence principle contradicts common sense, which builds on everyday experiences of very light objects falling much more slowly than heavier ones. Although Galileo's experiment is mentioned in most textbooks, the equivalence principle seems to be forgotten. In this paper, we present in some detail investigations of falling objects performed by ten-year-olds, and documented using iPads. We then give other examples of easily accessible investigations and observations relating to the equivalence principle. Demonstrations of free fall phenomena and teaching-learning sequences for older students have been proposed in many earlier works [e.g. in 6–10]. Recently Christensen *et al* [11] performed a careful analysis for balls falling in air. By comparing predicted and measured times for tennis balls of different weights, they concluded that the difference in drop times would have been clearly noticeable in Galileo's legendary experiment from the Pisa tower.

2. What factors influence how bodies fall? Investigations by middle school students

A video clip from the Cliff Diving Worlds Series 2013, in Copenhagen⁶, was used to capture the initial interest of a group of ten-year-olds for investigating falling bodies. One of them noted that it

must hurt to bellyflop from that height, leading to a discussion about how speed increases with distance, and the observation that falling 40 m gives a speed of 100 km h^{-1} when you land. The class also considered the question whether lighter divers would have more time for their movements on the way down, and decided to investigate how mass and size influence the fall.

The students decided to compare two objects at a time, using eyes and ears to detect any difference, rather than measuring the time for different objects to fall a certain distance. Comparisons were planned between eight pairs of objects with the same size and shape but a different mass; the same shape but a different size and mass; or, the same mass but a different shape. (A useful addition to this list might have been to bring objects with the same density but different mass and/or shape).

The teacher brought up the question of how small differences could be detected. One student then suggested using an app⁷ with the iPads to record the drop, making it possible to view the experiment in slow motion. The objects were taken along to the sports hall of the school and dropped from the stage, allowing for somewhat longer falls, as seen in figure 1. Each group of three to four students was asked to perform the experiments with the different pairs of objects and record the events on their iPads.

An advantage of filming the experiments is that you can go back and look at them over and over again. This can be useful if different groups have different results or when the groups have made different observations. This may be due to differences in how the experiments were performed, and the films may help to reveal these differences. Sometimes, the films do show the same results, but the students may have interpreted them differently. Showing the movies on a projector enables the students to work together to identify any differences in how the experiments were performed and to share their observations. The films also make it easier for the teacher to highlight critical aspects to note from a physics point of view and discuss these with the students, also afterwards. This is important since previous knowledge and experience influences what is observed and may affect what conclusions are drawn from the observations.

⁶ See, e.g., 'Best Dives' from Red Bull Cliff Diving 2013—Copenhagen www.youtube.com/watch?v=kTRuV0yRkqI.

⁷ Slopro, itunes.apple.com/us/app/slopro-1000fps-slow-motion/id507232505 was used for these experiments.

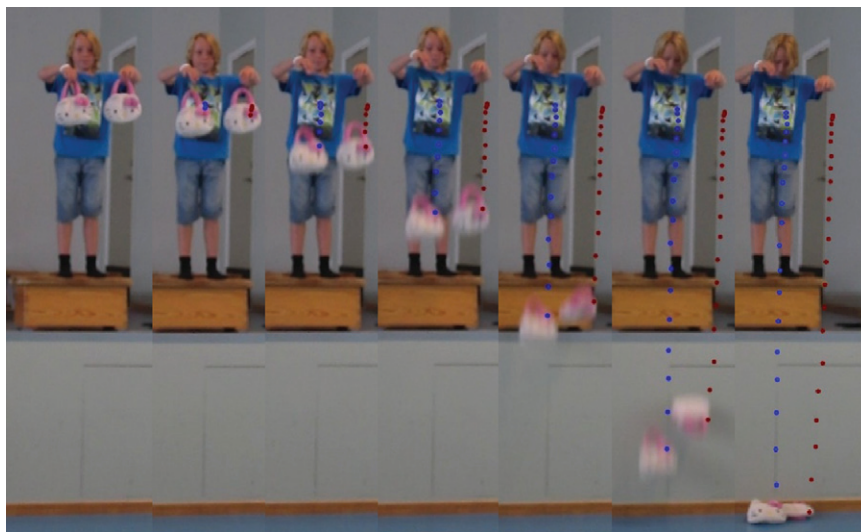


Figure 1. A sequence from a video of two ‘Hello Kitty’ bags falling, one empty and one with a golf ball inside. The Logger Pro software⁸ was used for frame by frame analysis of the two bags. Note how they fall closely together in the beginning.

3. Follow-up discussions in the classroom

Before the follow-up discussions of the experiments, the teacher asked all groups to review their video clips and consider what possible conclusions could be drawn. This was not so easy. For a golf ball versus a pingpong ball, the results were clear: the golf ball always came first. Similarly a single coffee filter always fell slower than two or more filters placed together. However, many of the other pairs seemed to land together. For the ‘Hello Kitty’ bags, empty or with a ball inside, some videos seemed to show them landing simultaneously, whereas in other cases, the empty bag rotated and fell more slowly, as seen in figure 1, where we have also used Logger Pro software⁸ for video analysis. What conclusions could be drawn from these observations?

The teacher raised the question about possible similarities between the pairs of objects that fell differently. A consensus was reached that in all these cases it seemed like the heavier object fell straight down, whereas the lighter object was seen to flutter back and forth on its way down. What was it that held these objects back, resisting the motion? The answer was quick: ‘The air interferes’. After some discussion everyone seemed to have accepted that the air was clearly influencing motion in the cases where objects fell differently.

What would happen if we could remove the air? One student stated: ‘I think they would have

⁸ Vernier Logger Pro, www.vernier.com/products/software/lp/.

landed together’ and many classmates agreed. It was interesting to note that these pupils must have changed their opinion about the influence of mass, from the initial expectation that heavier objects would fall faster, to the view that everything would fall together, independent of mass, if air resistance could be neglected. Other students, however, thought that the results would be different, still expressing the intuitive ‘Aristotelian’ view that mass influences the acceleration of falling objects.

The Moon has no air. What would happen if we went to the Moon for our experiments? The pupils were amazed to see the Apollo 15 video clip of a falcon feather and hammer drop on the Moon [1]. They also connected the result to other situations, noting, e.g., that in the absence of air, parachutes would be useless.

We conclude that students need scaffolding to be convinced that the physics textbook is correct in claiming that everything would fall in the same way in the absence of air resistance. Additional experiments to support this insight might involve comparisons between the ‘winners’ in the different ‘races’.

4. Exploratory talk as learning tools

From the teaching sequence, we believe that we can see how the students’ knowledge about the phenomenon is increasing. Their thoughts form the



Figure 2. The wave swinger ride, found in many amusement parks, provides a striking example of the equivalence principle: note how empty and loaded swings form the same angle to the vertical. (The wave swinger in the photograph is found in Gröna Lund, Stockholm.)

basis for the design of the investigations and also for the formulation of the results, giving them a feeling of ownership [12]. However, it is also clear that the teacher plays a crucial role in the scaffolding of the students during the different parts of the investigations and discussions. The scaffolding concerned scientific descriptions of the phenomenon, but was also essential for developing tools for reasoning, argumentation and reaching agreements concerning questions in natural science.

Mercer *et al* [13] describe how students need to be able to take part in *exploratory talks* in order to develop the ability to carry out and follow scientific reasoning. In exploratory talks:

- all relevant information is shared;
- all members of the group are invited to contribute to the discussion;
- opinions and ideas are respected and considered;
- everyone is asked to make their reasons clear;
- challenges and alternatives are made explicit and are negotiated;
- the group seeks to reach agreement before taking a decision or acting.

This approach was used both during the the initial discussion in the classroom, formulating questions and planning the experiments, and during the follow-up discussions, when different results were compared and contrasted.

After working with falling objects, many students referred to the joint classroom discussions as occasions when they became interested and learned something new. The teachers found this a bit surprising, having experienced or believed that it is the experiments/investigations that are perceived by the students as most interesting and enjoyable. A possible interpretation is that the students find the systematic investigations more meaningful with scaffolding, not only for the experimenting itself, but also for connecting everyday experiences with the result from a scientific perspective. The movies on the learning pads, and also the students' discussions around them, can be viewed as important tools for learning.

5. When mass does not affect motion

To Newton, it was obvious that mass does not play a role for motion affected only by gravity. Evidence could be found in Kepler's third law of planetary motion and in the motion of the Jovian moons discovered by Galileo. Newton also considered pendulum motion, where only gravity causes the pendulum to gain or lose speed—finding, of course, that mass does not influence the period (although the mass *distribution* does). This independence of mass of a pendulum can be illustrated with simple objects on strings or on a playground, where a child sitting low can

swing together with an empty swing. Children sometimes refer to the swinging together as ‘twin swinging’—when amplitude, period and phase coincide. (If the child instead stands up, it becomes obvious that the pendulum length influences the period.)

The common wave swinger ride in amusement parks (figure 2), where the angle of swings can be observed to be independent of mass, is a small scale illustration of the experiment by Eötvös, who used the Earth as a ‘carousel [14]’.

In an earlier paper [15], we demonstrated how 11-year-olds were able to reach the surprising conclusion that mass does not influence accelerated motion down a slide. Another playground experiment [16] exhibiting counterintuitive mass independence is to roll solid cylinders or balls of different size and/or materials together down a slide.

Environments outside the classroom thus offer many possibilities for discovering situations where mass does not influence motion—the equivalence principle in action.

6. Discussion

‘Null experiments’, such as the search for the effect of mass on motion under gravity, are a very special category, practised by a number of excellent physicists searching for small deviations, e.g. from the equivalence principle [3, 4]. Other examples include the charge of the neutron and electric dipole moments of elementary particles. In all these experiments, a direct measurement of differences is much preferred to a comparison between separate measurements. In the classroom experiment investigating falling objects, this corresponds to letting one person drop two objects simultaneously. This is therefore an important experimental methodology discussed and used by students, also giving them knowledge about the processes of science, and about how investigations can be done in practice.

In the study of falling objects air resistance does affect motion. The teacher has a choice of how to proceed from this observation. One possibility is to investigate the cause of the difference. In this work, the students compared different cases, discovering that some pairs of objects landed together, whereas in the cases where one object fell slower, the effect of air resistance was clearly observable. This variation was essential

and the comparisons paved the way for an appreciation that all objects would fall together in vacuum. In this way the students’ everyday observations could be reconciled with textbook claims. If only objects with negligible air resistance had been chosen for the experiments, this reconciliation would have been less likely.

An important development by Galileo was idealization—in this case, considering what would happen without air resistance or other sources of energy loss. In a thought experiment, he considered how the fall would be affected if two falling objects were joined together and concluded that mass would not influence the fall [5].

The discovery of the non-influence of mass in many different situations has deep significance, marking gravity off from all other forces. The equivalence principle is mentioned in relatively few textbooks, even at the undergraduate level. When mentioned, it is often in connection with the general theory of relativity. The *weak equivalence principle* between inertial and gravitational mass is then generalized to the *strong equivalence principle*, between gravity and accelerated systems [2]. This applies also to light, as presented in a very accessible form by Stannard [17].

Through scaffolding by the teacher, classroom investigations can be pushed just a little bit further, allowing students the opportunity to discover the consequences of the equivalence principle. Students can learn about ‘null experiments’ as a part of physics. The investigations can be a way to integrate aspects of both history and the nature of science, with connections to current research.

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