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How do we know that the Earth spins around its axis?

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Abstract

A carousel gives possibilities to explore physics in rotating systems and to gain first-hand experience of methods to measure rotation, without the need for an external reference. This paper discusses the Foucault pendulum, as well as the sideways deflection of horizontally and vertically moving objects in a rotating system. These experiments lay the foundation for an understanding of ways to demonstrate that the Earth spins around its axis.

Introduction

Sunrises and sunsets have happened day after day, year after year, since long before man was there to observe them. The Sun has risen and set long before telescopes and astronomical observations made us see Earth as one of the planets orbiting the Sun, and revealed that the Sun is only one of the stars in one of an immense number of galaxies in the Universe. Only during the last few hundred years has mankind known that it is the rotation of the Earth that leads to the apparent motion of the Sun across the sky. Our change away from a geocentric world view has not modified the use of the words sunrise and sunset. Still, the Copernican revolution has penetrated our minds so that most of us would take the observation that we have day and night as evidence for a rotating Earth.

But how do we know? Anyone who has observed Foucault's classical pendulum in the Pantheon in Paris, or a science centre or science museum version, is unlikely to forget the slow, very slow, change of direction of swinging relative to the floor. Most of our new students have not seen it. We could shift the question of the spinning Earth to focus on how we can know if anything rotates. The need for a centripetal force to keep the body in a circular motion is felt in the body of anyone in a swing or in a fast-moving carousel, although the experience is often discussed in terms of a centrifugal force. In a slow carousel or rotating tower, this effect is not very conspicuous. On the other hand, the much less familiar Coriolis effect for bodies moving in rotating systems can be observed in simple and small-scale experiments, that are still quite spectacular. The experiments can be performed in an amusement park or with a local playground carousel, where the playground has the advantage of easier access. It can be visited more frequently, and experiments can be repeated if additional questions arise during follow-up discussions after the visit. In addition, safety considerations are less stringent in a playground, which makes it possible to bring more objects into the rotating systems.

Recently, I invited a class of fourth-graders (10–11-year olds) to experiment at a large playground in Göteborg. Experiments were performed in carousels, as well as on swings and slides (Pendrill and Williams 2005) and in a climbing rack. At the end of the visit, the whole class sat down and discussed the experience before returning to school, and I asked what experiments had surprised them most. They agreed that the experiments using the carousels had made the

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Figure 1. A pendulum experiment with a cuddly toy on a string in a playground carousel.

strongest impression. This paper discusses these experiments.

Experiments in slow carousels

A children's carousel, a rotating panorama tower or a loading platform for a water ride are all examples of slowly rotating coordinate systems, suitable for illustrations of the same principles that are used to demonstrate the rotation of the Earth. In this section we first describe a miniature version of the Foucault pendulum and then continue with experiments exhibiting the apparent sideways motion of objects moving horizontally or vertically in the rotating system.

A miniature 'Foucault' pendulum

Find a small cuddly toy and get a string, about half a metre long. Tie the string to the toy. Take your toy on a string to a nearby playground or amusement park with a carousel that can rotate very slowly. If the carousel is of the type shown in figure 1 (Granström 2001), you will also want to bring a couple of friends, one for the other side, and one to set the carousel in motion. Board the carousel. When the carousel is moving, hold the end of the string in one hand and use the other hand to start the pendulum motion of the cuddly toy. If you identify a good landmark visible from the carousel, you may want to start the pendulum motion in that direction. Observe the motion of the pendulum. What do you think will happen?

Adults without physics training often have difficulties with the pendulum experiment. Instead of letting the object swing, they typically let it hang still and wait for it to move outwards when the carousel starts. Adults know what happens when things go around. However, of the inertial forces appearing in a rotating system the centrifugal force is not very eye-catching in a slow carousel, whereas the Coriolis effect for moving objects makes the pendulum experiment rewarding for those who follow the instructions. I have observed 8-year olds coming off an amusement park carousel and excitedly telling their friends and teachers that 'It made a star, it made a star'. Another 8-year old described how the pendulum in a panorama tower kept moving towards a tall building in the harbour. When asked to explain the motion he said that it would not have moved like that if it had instead been the windows and everything outside moving around the tower.

Figure 2. Two fourth-graders throwing a ball in a playground carousel which rotates counter-clockwise. In the first attempts, the ball arrives behind the person on the other side.

The pupils in the playground were absorbed by watching the little pendulum swing, as in figure 1. Earlier work (Bagge and Pendrill 2002) presented the results of interviews with another group of 10-year olds three months after an amusement park visit which included carousel experiments. The visit had taken place just before Christmas, and the class teacher was concerned that he did not have time to follow up on their experiences in the park. During the group interviews, many of the children recalled the pendulum in the carousel, and also that it had something to do with the rotation of the Earth, commenting, for example:

'In the Pony Carousel, the cuddly toys on the strings started to move like this. I think it was to prove that the Earth is rotating'.

This quote was accompanied by drawing a star in the air. During the visit, one of the teachers in the class had brought up the question of why we would do this, so the question how we can know that the Earth rotates was discussed. For some children, this discussion had made a deep impression.

'I learned that when going in the Pony Carousel, the cuddly toy kept going in the same direction while I was going around'.

Here, the response indicates an awareness of two different system, one rotating and one non-rotating.

Weather patterns and projectiles

With very little preparation, a playground carousel can be used for other experiments. Figure 2 shows two children throwing a ball in a rotating carousel. The additional friend who sets the carousel in motion also needs to pick up the ball, which tends to miss the friend on the other side of the carousel the first few times it is thrown.

In the discussion after the experiments, they children could describe how they had figured out that they needed to throw the ball a little bit to the front of the friend on the other side, since he would have moved around a bit before the ball arrived.

(The fact that the ball has an initial sideways velocity due to the rotation was not brought up.)

On special occasions, experiments requiring additional preparation might be performed in an amusement park. Mühlen *et al* (1999) describe experiments in the Gröna Lund amusement park, where a water pistol was mounted in a preconstructed rack, so that the water was shot towards the centre of the carousel. In another experiment an airgun and a shooting target were mounted under a carousel horse, and the difference in arrival points for a stationary and rotating carousel could be clearly discerned.

Deflection of falling objects in rotating systems

A carousel with vertical poles makes it possible to study the sideways deflection of falling objects in a rotating system. Mühlen *et al* (1999) mounted a device on a carousel pole to drop little marbles onto carbon paper, leaving a track of the landing point, so that the deviation due to rotation could be noted (figure 3). The horizontal motion of the marble is most easily described using Newton's first law. When the marble is dropped, is will continue along a straight line with its tangential velocity, $r\omega$, if viewed by an imagined stationary overhead observer. This motion will bring the marble slightly further from the centre of the carousel, where its speed will be insufficient to keep the same angular velocity as the carousel. The landing point for the marble will thus be slightly outside and behind the pole.

An analysis of the motion of the marble using inertial forces must include both the 'centrifugal' force and the 'Coriolis' force. Since the Coriolis force is proportional to the velocity component orthogonal to the axis of rotation in the moving system, the downward motion, being parallel to the axis, does not contribute. The initial outwards deflection is a consequence of the centrifugal force. The resulting outward motion, as seen from within the moving system, can then lead to a contribution to the Coriolis force, giving rise to the apparent backwards deflection.

The experiment with marbles falling in a carousel can be seen as a simplified miniature version of an experiment suggested in the 17th century as a way to prove or disprove the rotation of the Earth, as discussed in detail by (Persson 2003, 2005). During the winter in 1678–1679, Newton and Hooke debated the trajectories of falling objects. Thanks to Hooke, Newton came to the insight that a falling body would follow an *elliptic* orbit. In 1803, pebbles were dropped into a 90 m deep mine shaft in Schlebusch in Germany.

Figure 3. An experiment to measure the deviation of a falling marble when the carousel is in motion.

Gauss and Laplace had made a prediction of an expected 8.8 mm deflection. The average observed deflection was 8.5 mm (Persson 2005).

In an introductory project work for first-year university physics students, we once asked them to find out more about the motion of the Earth, including ways to detect rotation. A few of the groups had found a reference to the deviation of objects dropped from a high tower. None of them had attempted to estimate the effect. After their project presentations, we interviewed all students, two or three at a time. Students from the groups that had proposed dropping objects from a high tower were all asked about the size of the effect. The answer, invariably, was 'small'. When asked if is would be 'an angstrom or a metre', they kept insisting on their original answer, 'small'. Would they be able to calculate the effect? Most groups were able to describe how the effect would arise since the top of the tower moves faster than the bottom. They thought they could work it out in less than half an hour.

An examiner hearing that students, in a project spanning a couple of weeks, did not perform a calculation they thought would require less than half an hour obviously asks 'Why did you not?'. An important key is that all students first asked us to provide them with a specific tower, including its latitude and height, h. Had the problem appeared as an examination problem, the question would be well defined and already have been prepared to include this information, or at least introduced notations for the relevant variables. The students would then possibly have found the answer that the falling object would have an excess horizontal velocity Ωh at the equator, which over the time of the fall would carry the object a horizontal distance

$$\Omega h\sqrt{2h/g}.$$

Away from the equator the effect is reduced—it is directly proportional to the cosine of the latitude. By formulating a well-defined question, including variables of interest, we would never have discovered that it was the problem formulation, itself, that was problematic for the students.

In fact, working out the deflection of a falling object in the simple way described above gives an answer that is 50% too large. During the fall, the direction of the force of gravity changes, to continue to point to the centre of the Earth. The resulting backward acceleration can be written as

$$a = -g \sin \Omega t,$$

to be integrated over the time of the fall, t. Although this may seem like a small effect, it cannot be neglected in a calculation of the small deflection (Persson 2003).

For the experiment with a marble dropping in a carousel, no complication arises due to the changing direction of gravity. The observable effect is due only to the rotation of the carousel.

But do they learn anything?

At what stage is it suitable to introduce discussions of how we can know that the Earth rotates or about forces in rotating systems? The understanding of how we can know that the Earth rotates is not critical for everyday life, but can give a good illustration of how science can distinguish between alternative explanations for a phenomenon. The section *Student views on the rotating Earth* presents replies of new students to the question of how we can know that the Earth spins around its own axis.

Questions about how we can detect the rotation of the Earth are not part of the school curriculum, either for 10-year olds, or for 18-year olds. Even college text-books tend to omit this discussion. The section *Nature of science* discusses how the question of the rotating Earth can be used to illustrate the 'nature of science'.

Student views on the rotating Earth

As part of introductory diagnoses for new university students, I often include questions of the type 'How do we know...?', including the question about the spinning Earth. The most common answer is that 'we have day and night'. Some students in non-science courses tend to give standard answers, such as 'researchers have found' or 'through experiments and observation', to all questions of this type.

In this section we analyse replies from first-year engineering physics during their first week at the university, before they have had any physics classes. The engineering physics

Table 1. Replies to the question 'How do we know that the Earth spins around its axis?'. Group I received the question in this form. For group II, the line 'i.e. that it is not the Sun moving around the Earth' was added, to encourage them to look beyond explanations referring to 'day and night'.

Group	Pendulum + Coriolis or weather	Universe + Planets	Newton	Day and night	Seasons	Other	No reply
I ($N = 110$)	4 + 3	12	5	26	2	6	58
II ($N = 122$)	6 + 3	39	12	11	21	17	34

students are quite an unusual group of first-year students, as indicated for example by their entrance score on the often used 'Force Concept Inventory' (Hestenes *et al* 1992, Hake 1998), which consistently lies around 80%, before any courses at the university.

Table 1 presents a classification of answers given by engineering physics students. First, replies are presented from a group (I) of 110 students to the question 'How do we know that the Earth spins around its axis?'. The second group (II) of 122 students were given an additional line in the question 'i.e. that it is not the Sun moving around the Earth'.

From the table we can see that less than half the students (52 of 110) answered the original question, whereas more than 70% (88 of 122) gave at least one answer to the more specific question. In both cases, only a small number of students (7 and 9, respectively) mentioned the Foucault pendulum or the Coriolis effect or weather systems.

When students were asked (at least implicitly) to look for other replies than day and night, the answers referring to the difficulty of the Universe or planets moving around the Earth were more common and more elaborate. In addition, a larger fraction of the students then looked to the seasons for explanation.

A small number of replies (5 and 12, respectively), were classified as referring to Newton's laws. These included replies that compared the masses and gravity of the Sun and the Earth, the difference in gravity or radius between the equator and the poles, or discussed the orbits of spaceships. Two replies from group II, classified as 'other', referred to the Earth's magnetic field.

A few students brought up more than one way to detect the rotation, for example:

'We can see that we rotate relative to other stars and galaxies, which could not all move equally fast around the Earth. At a certain altitude, satellites can be geostationary, without losing altitude. This indicates a rotation, where the acceleration of gravity acts as a centripetal acceleration'.

'By studying the sky. Also by measuring the variation of gravity over the Earth. It is lowest at the equator due to the rotation'.

Among the replies that were classified as 'other' in table 1 were a few (3 and 4 respectively) referring non-specifically to 'observations'. In group II, the 'other' results also included two replies referring to Galileo's explanations, four replies claiming that rotation is relative, and one reply noting that 'I have never thought about it'.

We conclude that the knowledge about how to detect the rotation of the Earth is not widespread even among our top new physics students. Still, we have seen from interviews and discussion that even young learners can appreciate experiments designed to demonstrate the rotation of slow carousels, and be fascinated by the connection to the demonstration of the rotating Earth.

Nature of science

The question 'How do we know?' can be applied to many phenomena of different levels of difficulty and at all levels of education, and is an essential part of scientific work. The question about the rotating Earth also illustrates other aspects of a scientific approach.

Another aspect of scientific work is to make quantitative predictions for planning an experiment and comparison of results. In the case of objects dropping from a high tower, discussed in the section *Deflection of falling objects in rotating systems*, a scientific approach would include working out a formula, and picking a high tower with some 'typical values' to determine if the experiment would be feasible. We find that this aspect needs to be given further attention in education.

Discussion

Would it be possible to introduce concepts, known to cause difficulty for university students, at a much earlier stage? Driver *et al* (1994) note: 'There is considerable support for allowing pupils to develop their own dynamics—to clarify and label their own ideas. This is seen as a process which could begin early and which should precede any attempts to teach formal physics concepts, and which is better with 11-year olds than with 14-year olds!'. The variation in the ways to learn mechanics can be expected to lead to a deeper understanding and more transferrable skills (Marton and Booth 1997).

In planning lessons for young learners, it is natural to build on strongly visual experiments and, if possible, also on the experience of the body. What can be learned by fourth-graders (10–11-year olds) from a lesson in a playground or in an amusement park? Earlier group interviews in connection with such activities have been analysed, for example, by Bagge and Pendrill (2002), Nilsson *et al* (2004), and Nilsson (2005).

The carousel experiments described in this paper give first-hand experience with the fictive 'Coriolis force' acting on objects moving in a rotating coordinate frame. The Coriolis force is certainly not part of the school curriculum. When students encounter the mathematical treatment at university, in general, they have no direct experience of it, and find it a very abstract phenomenon, with little relevance for life or technology. Still, experiments in slowly rotating systems have been found to fascinate 10-year old learners, as well as older students. Find a playground close to you and try them out!

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