Student Understanding Of Gravitational Potential Energy And The Motion Of Bodies In A Gravitational Field

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We have been investigating student understanding of energy concepts in the context of introductory courses for non-science majors as well as those for science and engineering majors. We have found that many students develop incomplete and incorrect understandings of the concept of gravitational potential energy. Moreover, students often have incorrect notions about the motion of bodies under the influence of gravity. These incorrect beliefs may prevent the development of a coherent understanding of energy as a conserved quantity.

INTRODUCTION

Energy is a fundamental concept in physics and physical science courses at all levels of the curriculum. In particular, the concept of gravitational potential energy (GPE) and descriptions of the motion of bodies in the presence of a gravitational field are taught in courses at every level from graduate level physics down to elementary school.[1] As part of an ongoing study of student conceptions of energy, we have sought to characterize student understanding of specific situations that are often covered in physics and physical science courses. There is considerable evidence to suggest that students conceptualize energy quite differently than do physicists.[2,3,4] Informal discussions with students in class suggested difficulties with the standard physical explanation of the motion of a body in a gravitational field and even a failure to understand the variables on which GPE depends. We sought to document and analyze student difficulties and characterize student thinking.

Context for research

This study was performed in the context of courses at a public comprehensive university serving a diverse student population. Two sample courses enroll primarily non-science majors. The Course for Teachers is a physical science course for pre-service elementary school teachers. This course is taught in a lab-based, guided inquiry format, meeting six hours each week. All students are planning to teach at the K-8 level. The Survey Course is taken by students in order to satisfy a general education requirement. It includes three hours per week of traditional lecture and has an optional three-hour lab component. A third course, which we will call Introductory Mechanics, is a fairly typical introductory mechanics lecture and lab course for science and engineering majors, with three hours of lecture and an traditional three-hour lab.

In all courses, students were taught a model for energy conservation including the following features: definition of a system, potential and kinetic energy, and transfer of energy into or out of a system, including work. All students had been taught explicitly the formulas for GPE and kinetic energy (KE), with particular emphasis that GPE depends on mass, height above a reference point, and the strength of the gravitational field (which was assumed to be constant unless specified otherwise). The treatment in the course for science majors was considerably more quantitative and included the solution of standard numerical problems, and students had completed two labs on energy topics, one on collisions and the second on a ballistic pendulum. Unless otherwise noted, students had completed all instruction on energy at the time they completed the research tasks.

RESEARCH METHODS

All data in this paper were collected by analysis of student responses to free-response written questions posed on course examinations and ungraded quizzes. The questions were constructed so that incorrect answers would correspond to the incorrect ideas we had observed in informal interactions with students. Students were asked to provide an answer as well as an explanation. Student answers were recorded and explanations were classified and assigned codes. The major categories of student answers and explanations are described below.

GPE AND MOTION OF A BODY

The initial focus of this study was student understanding of the periodic motion of bodies in the presence of a gravitational field, as in a simple pendulum. Therefore we posed problems in which students were asked to make predictions about this motion in various situations. For example, students are asked to predict the final height of an object released from rest, either a simple pendulum or a ball or block sliding in a frictionless bowl. Students are told that the object is released from rest and asked whether the level at which the object comes to rest (on the opposite side of its first cycle) is *higher than, lower than, or the same height as* the point of release. Students are explicitly asked to ignore the effects of friction and air resistance. Table I shows responses from several height comparison problems.

Belief that final height will be greater

In each set of responses, at least one in eight students predicted that the final height would be *greater than* the initial height. These responses raise a question whether students are in a position to develop a good model for the behavior of this system. The energy description of this system is based on observations of the motion of bodies like a pendulum, but the belief that the final height is greater explicitly contradicts conservation of energy.

Students giving this response frequently appeared to use a colloquial association of energy with activity. For example, one student making such a prediction explained: "The height will be greater because the ball gains energy in the swinging process." Other responses included the term momentum: "As the pendulum continues in its motion, I believe the maximum height will be slightly above point A due to the momentum built up as it swings back and forth." Another student wrote: "It will be higher because it is getting more momentum (energy is being transformed to kinetic energy) so it will be pushed upward more."

Final height will be less

At least 20% of the students predicted that the final height would be lower, even when explicitly asked to neglect the effects of friction and/or air resistance. The explanations given by a few of these students suggest that they may have misunderstood the problem statement and considered friction. However, many explanations suggest that these responses reflect more than a mere misunderstanding of the assumptions in the problem. For example, one wrote, "Below the release point because even though friction and resistance is disregarded, there is still gravitational energy that is pulling down on the ball as it rolls to the opposite side." Another wrote, "It will be below due to the fact that it is using energy as it swings so when it swings back it is below the beginning place."

These responses raise some questions about development of the energy model. Can these students distinguish the actual motion of a pendulum with resistance from the motion of an idealized system without resistance? The first answer above seems to indicate confusion between energy and force, and indicate that the gravitational force, rather than friction, eventually causes a pendulum or ball to slow down and stop. This notion led to the additional questions described in the next section.

TABLE 1. Student responses to written problems. All numbers rounded to the nearest 1%.

	Pendulum	Ball in Bowl	Ball in Bowl	Ball in Bowl
Max height after first half-cycle will be:	Course for Teachers ($N = 48$)	Survey of Physics ($N = 40$)	Course for Teachers ($N = 25$)	Calc-based Mechanics ($N = 36$)
Same height	52%	18%	64%	67%
Lower	35%	70%	20%	22%
Higher	15%	13%	16%	11%

WHY DOES IT STOP?

Based on the results described above, we asked additional questions that stated explicitly that the object eventually stopped moving. Students were then asked to give an explanation of this behavior in terms of the concept of energy. Similar problems have been posed by other researchers.[5]

A physicist would say that the swinging pendulum comes to rest because of a decrease in the mechanical energy of the pendulum-earth system; the forces of interaction between the ball and the surrounding air act to transfer energy from the ball to the air and to increase the systems' internal energy. Student responses often differed considerably from this ideal.

Belief that energy is used up or consumed

Many students in their explanations referred to loss, consumption, or use of energy. When asked to explain why the pendulum eventually came to rest, one student wrote, "…the energy gets weaker and weaker. When the pendulum finally stops, it mean there is no energy at the end." Another wrote: "The pendulum uses all of its energy… After release its gravitational potential energy and its kinetic energy are both being used. Since the pendulum is being pulled down by gravity both energies decrease after each swing."

Belief that 'gravity' or GPE stops objects

In both the pendulum height and 'why does it stop' questions, many students identified either 'gravity' or GPE, rather than friction or air resistance, as the agent that eventually causes bodies to stop moving. The language used by students is imprecise, so it is difficult to know whether the term 'gravity' refers to a force, a field, or to GPE. In one section of the Survey of Physics (N = 69), 45% of students identified one of these in a question asking why a pendulum came to rest. Only 39% gave explanations classified as correct. One student wrote, "The gravitational PE energy will eventually pull the pendulum to rest," suggesting confusion between energy and force. Another response suggested that GPE would be greater after the pendulum had stopped, "The pendulum loses kinetic energy and gains potential energy as it slows down to its resting point."

In some cases, these students also identified friction and/ or air resistance. They certainly identify gravity, rather than any resistive force, as the ultimate cause of the stopping. Responses to these problems are consistent with previous research results.

HEIGHT DEPENDENCE OF GPE

The responses described above led us to pose additional questions. In particular, some responses suggested confusion between GPE, gravitational force, and the more general notion of 'gravity.' Thus we asked questions involving comparisons of GPE for objects of the same mass. Results from final exam questions suggest that, even at the end of a course, many students do not understand that GPE depends only on the mass and height of an object (given a constant gravitational field). Many students seemed to be distracted by the motion of bodies or by the presence of additional forces on the bodies. Therefore we developed questions to probe whether students could correctly apply the definition of GPE despite these distractions.

Students in the Survey of Physics course (N = 51) were asked to compare the GPE of the five balls in Figure 1. Only 21% gave correct rankings. Students in the Course For Teachers (N = 24) were asked to compare the GPE of the two identical balls in Figure 2, one of which is at rest on a ledge and one of which is moving downward. One third answered correctly. Below we examine common incorrect answers and explanations.

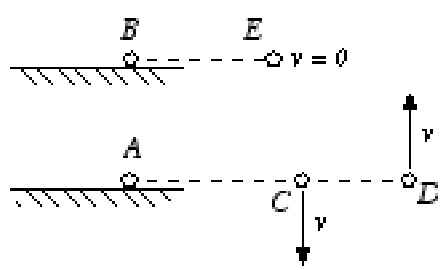

FIGURE 1. GPE comparison for five identical balls with different heights and velocities. Students were asked to rank the GPE of the ball-earth system for each of the five balls.

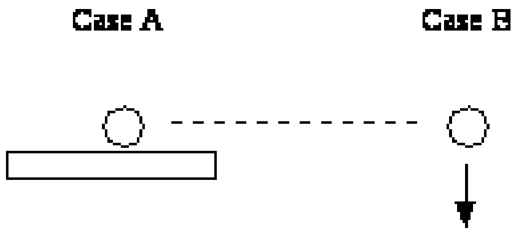

FIGURE 2. GPE comparison for two balls. Students were asked to state whether the GPE in the ball-earth system was greater in case A, greater in case B, or equal in the two cases.

Belief that GPE is influenced by motion

Only 25% of the students in the Survey of Physics course ranked balls A, C, and D correctly. Approximately 40% of students stated that ball D, moving upward, would have a greater GPE than ball C, moving downward, despite their equal height. Some students placed the GPE of ball A between the two, and others found it to be the least of the three.

In reponses to the two balls question, a number of students in the Course for Teachers stated that ball A would have more GPE and referred to the motion of ball B in their explanation. One such student wrote, “A>B, because the ball is at rest at the top of the ledge at A, while the ball is moving downward in case B.” Some explanations may reflect a misapplication of energy conservation: “B is actually moving so its energy has transferred to kinetic energy, not just GPE like A.”

Belief that GPE is influenced by support:

Student responses to the problem shown in Fig. 2 suggest that many students believe that GPE is influenced by the presence of a supporting object. For example, one student wrote: “In case A the ball is on a ledge, therefore doesn’t have any [GPE]. In case B it has the ability to drop and is above the ground so therefore has a greater [GPE].” Students gave this response even while noting that the balls are at the same height: “Case A has the ball securely on a stable setting, it GPE is much less than in case B, where it is sure to fall. Although they are at the same height, B > A with gravitational potential energy.” Responses of this sort echo a common student statement in class, that GPE and other forms of potential enegy describe the “potential” for an object to move.

In responses to the problem shown in Fig. 1, approximately 60% of students stated that the GPE of balls B and E were different, with most stating that ball E would have the greater GPE. These responses are consistent with the explanation above and the notion that the supporting ledge influences the GPE of ball B. However, explanations were not very detailed.

SUMMARY AND FURTHER STUDY

Even the simplest questions on GPE proved difficult for many of the students in this study. Many students fail to recognize the variables on which GPE depends, and appear to be confused by the effects of external forces and the speed of a body. Many students make incorrect predictions about the motion of bodies under the influence of gravity. Finally, students fail to apply correctly the energy model in accounting for the cessation of motion under resistive forces. The current report is admittedly incomplete, but suggests that there is fertile ground for further examination of these questions. We intend to pursue these questions further, and examine student thinking on GPE in more detail. We have already performed preliminary interviews and posed additional written questions and will report additional results soon.

ACKNOWLEDGMENTS

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