Examining student ability to interpret and use potential energy diagrams

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1. Introduction

The Physics Education Group at the UW is examining the extent to which students are able to interpret graphs of potential energy vs. position for classical systems and use these graphs to infer kinematic and dynamic quantities about a system. A goal is to develop a tutorial [1] on potential energy. Broader motivations include preparing introductory students for advanced topics in classical mechanics and basic quantum mechanics, where potential energy diagrams are commonplace. In addition, this research extends the existing literature on student reasoning about energy.

2. Context and methods

Questions were administered to 500+ calculus-based introductory physics students and 100+ sophomore-level quantum mechanics students.

Formats include written & online pretests, multiple-choice & written final exams, and individual student interviews.

All relevant lecture instruction was completed prior to questioning.

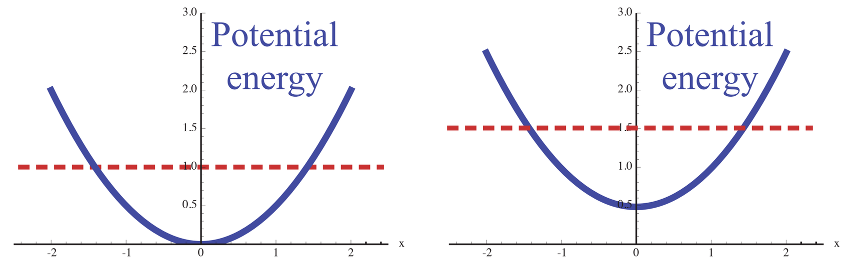
3. Research approach to energy

Potential energy was considered to be a property of systems, not individual particles [2].

All systems considered were one dimensional.

All systems considered were classical (non-relativistic) with $U(x)$ and $E_{tot}=K+U$ arbitrary up to a constant U_o [3].

Thus, for example, a simple harmonic oscillator may be represented by either of these potential energy diagrams.



4. Overview of questions asked of students

Student were asked to consider a particle that is part of a one-dimensional system.

The forms of energy in the system were stated to be potential energy of the system and translational kinetic energy of the particle.

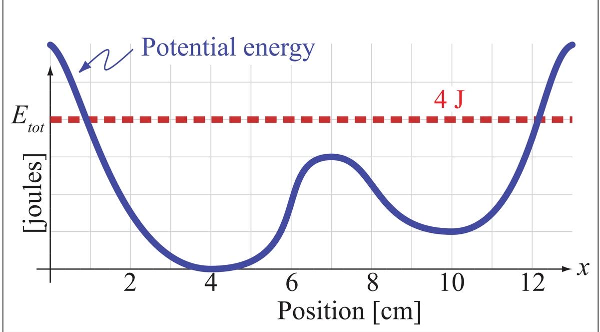
Students were told to ignore dissipative effects.

Specific questions posed to students are described in the following sections.

5. Student tendency to interpret $U(x)$ as $x(t)$

Between 10%–30% of introductory students treated potential energy diagrams as if they were plotting position and time:

Question: What is the direction of the acceleration at x = 6 cm?

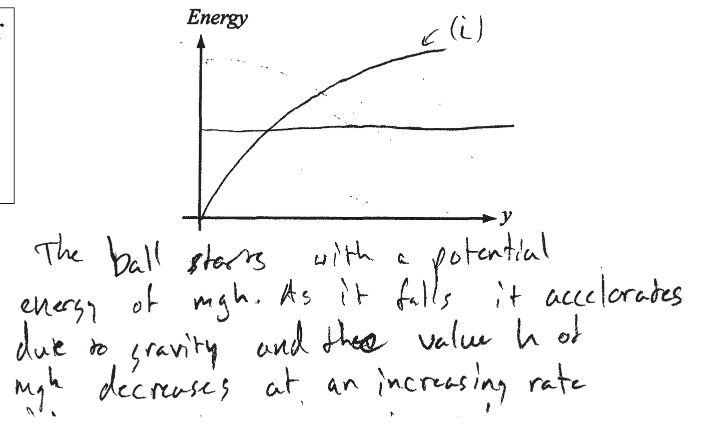


"[The acceleration at x=6 is zero since] the double derivative of the graph at x=6 is zero."

Not all students were consistent in treating velocity and acceleration as the first and second derivatives, suggesting that this tendency is not due to a simple misreading of axes labels.

In addition, roughly 20% of sophomore students drew curved graphs to represent the potential energy of an Earth-ball system. Many stated they were indicating that the rate of change of height of a falling ball increases as time progresses. Despite their curved graphs, some of these students wrote a correct linear expression for potential energy:

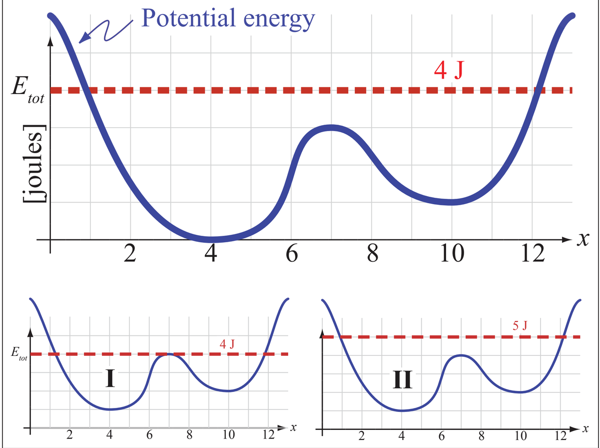
Question: A ball is dropped near the surface of Earth. Sketch, for the Earth-ball system, the potential energy versus height of the ball.



6. Student tendency to incorrectly apply conservation of energy

Between 10%–25% of introductory students believed that the numeric value of energy in a system is not arbitrary. Many of these students argued on the basis of conservation of energy:

Question: Which of the graphs I and II below could represent the same physical system as that of the larger graph and have the particle undergo the same motion (*i.e.*, have the same speed at every position)?



Answer: Only graph II.

"[Graph I is correct because] the system would have to have the same total energy [since] energy cannot be created or destroyed."

"[Graph I is correct.] [By] the law of con[s]ervation of energy, all energy is conserved."

7. Student belief that negative potential energy cannot exist (classically)

About 35% of introductory students believed that the potential energy of a system cannot be negative [4]:

"... you cannot have negative potential energy in a system."

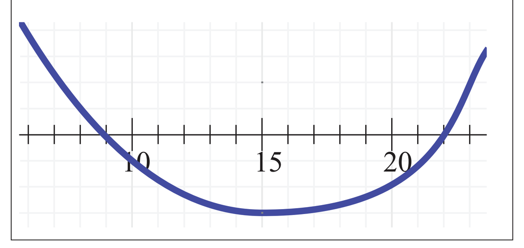
Justifications for this belief included arguing that mgh and $1/2kx^2$ were always positive. These students may not have realized that these expressions are positive as a result of a choice of arbitrary constant U_o.

Roughly 10% of sophomore students in a quantum course believed that negative potential energy was a feature unique to quantum mechanics:

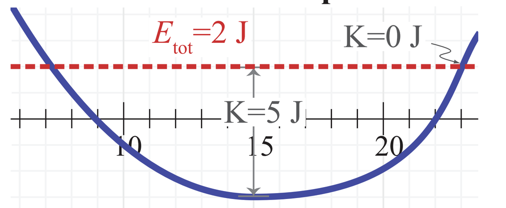
"... classically, there is no way to achieve a negative potential energy (that I know of)"

Other introductory students believed $U < 0$ was possible, but had difficulty reconciling this with the fact that the numeric value of kinetic energy $K=E_{tot}-U$ must then exceed the numeric value of total energy E_{tot}:

Interview question: A particle is released from rest at x=23 m. Describe the subsequent motion of the particle.



Possible correct description



Initially student believes $U < 0$ is possible:

"... they're negative, and that's fine."

Later he attempts to answer the question at left. He and many others believe $K_{max}=E_{tot}$:

"I actually know all of the energy that's in this system. It's 2 joules. ... [D]own at 15 [m] it has 2 joules of kinetic."

After the interviewer guided the student to realize K_{max}=5 J, the student tried to reconcile this with the E_{tot}=2 J and his ideas of conservation of energy:

"That doesn't seem okay at all, because you know [energy] has to be conserved ..."

8. Summary

A number of reasoning patterns and difficulties emerge when asking introductory students to reason using potential energy diagrams:

Students often determine kinematic quantities from potential energy diagrams as if the graphs were plotting position and time.

Conservation of energy is often used to argue that the value of total energy in a system is not arbitrary.

Negative potential energy can be unfamiliar to students. However, even students who believe negative potential energy exists can have difficulty in applying conservation of energy to such systems.

Some of these ideas appear to be strongly held even at the sophomore level. A curriculum designed to address these difficulties in an introductory setting may positively affect student performance in these more advanced courses.

[1] L. C. McDermott, P. S. Shaffer, and the P.E.G. at the U. W., *Tutorials in Introductory Physics,* Pearson Learning Solutions, 2010, Preliminary 2nd ed.
[2] J. W. Jewett, The Physics Teacher **46**, 81 (2008).
[3] See, for example, Ruth W. Chabay and B. A. Sherwood, *Matter & Interactions: Volume I*, Wiley, 2010, 3rd ed.
[4] Others have found similar results. See, for example, L. Bao, *Using the context of physics problem solving to evaluate the coherence of student knowledge*, Ph.D. dissertation, University of Maryland (1999).