Student Performance Q&A:
2001 AP® Physics Free-Response Questions

The following comments are provided by the Chief Faculty Consultant regarding the 2001 free-response questions for AP Physics B and C. *They are intended to assist AP workshop consultants as they develop training sessions to help teachers better prepare their students for the AP Exam*. They give an overview of each question and its performance, including typical student errors. General comments regarding the skills and content that students frequently have the most problems with are included. Some suggestions for improving student performance in these areas are also included. Consultants are encouraged to use their expertise to create strategies for teachers to improve student performance in specific areas.

Physics B

Question 1

The first question involved the analysis of circular motion in a vertical plane. In this version of a canonical problem, a tethered ball rotates through a vertical circle. Circular motion often poses a problem for students, and this question was no exception to that rule. Students found this problem to be slightly more difficult than B problems in mechanics on recent exams.

In part (a), students were asked to indicate the forces acting on the ball at two points in its trajectory. The most common error was the introduction of incorrect forces, or of irrelevant vectors, such as the velocity vector. In parts (b) and (c), the student was asked to analyze the motion at the top and bottom of the ball's trajectory in terms of Newton's second law. Sign errors were the most common source of student confusion in these two sections. In the last section, students were asked to describe the motion of the ball if the string breaks at a certain point in the ball's trajectory. The student responses fell into one of three categories: good answers, slightly flawed answers, and significantly flawed responses. In the slightly flawed responses, the students often conflated the term motion and trajectory. The significantly flawed responses indicated a lack of understanding, i.e., stating that the ball would move radially outward. As is often the case, students scored lower on a problem involving circular motion than they do on problems involving linear motion.

Question 2

The second free-response question involved the application of the principles of kinematics and conservation of linear momentum. The question was of average difficulty. What was surprising was the number of zeros awarded on this problem. More than one paper in eight received a zero, indicating that those students tried the problem, but were unable to earn any points with their responses.

Part (a) is an application of the conservation of linear momentum to a one-dimensional collision. The most common error here occurred when students attempted to apply the kinematic equations to a question that was not amenable to solution by that method. In part (b), a correct application of the kinematic equations did yield the correct solution. In part (c), students again used kinematics. Some students seemed confused by the diagram here and in part (d), where the conservation of linear momentum was again applied. The most common error in part (d) was the failure to resolve the momentum vectors properly. The inability of students to differentiate between situations where kinematics is applicable, and where the conservation of linear momentum is applicable, was the most common source of errors throughout this problem.

Question 3

The third free-response question was of above average difficulty for most students. The low scores were surprising in light of the straightforward nature of this problem dealing with the electrostatics of point charges. It is clear from the student responses that more work needs to be done on the electrostatics of point charges, the vector nature of electric fields, and the scalar nature of the electric potential.

In part (a) students were asked to find the electrostatic potential and the magnitude of the electric field at the center of a square that had four charges at its vertices. The four charges, two of +Q and two of –Q, were located at the vertices in such a way that the two values asked for were zero. In part (b), two of the charges exchanged positions, so that the value of the potential remained zero at the center of the square, while the electric field took on a nonzero value. Finally, in part (c), the students were asked to state in which of the two configurations more work would be required to move a specified one of the four charges to infinity.

The student responses indicated a lack of familiarity with calculating the electric field arising from a group of point charges. Most students did not realize that the electric fields of the individual charges add as vectors, while the electrostatic potentials add as scalars. Very few students had any idea of how to relate the work done to move a charge to the electric potential in part (c), with most arguments referring solely to the electric fields.

Question 4

Question 4 was an easier free-response question than average. Most students scored high on this question, and seemed to have little difficulty with the physical concepts. Those students that had problems seemed to have them on the graphical analysis section of the question.

Most students did well on all parts of this geometrical optics problem. Use of the graph in part (a) was the only part of the question that students had much difficulty with. It was difficult to tell if students could perform the graphical analysis that this section was designed to assess. Many students relied on a single point from the graph to determine the index of refraction. Part (b), which involved determining the frequency, speed of light in the glass, and the wavelength of the light in the glass, posed little problem for most students. Nearly all students were familiar with the relation $c = \lambda f$, but some seemed unfamiliar with the fact that the frequency of the light was the same in both the glass and the air.

Part (c) was straightforward, but the new line on the graph that students were to draw for a beam of violet light was very close to the line for red light already on the graph. This made the evaluation of student responses difficult in some cases. In the future a larger dispersion, even one that is physically unreasonable, should be used to make the graph easier to interpret. The final section of the question, the determination of the critical angle for total internal reflection, was easy for most students. This question discriminated well only among students of low ability, as students of moderate and high ability all scored well on this question.

Question 5

This question assessed the students' knowledge of laboratory technique involving electrical measurements. The student was provided with a list of equipment and a graph of resistance versus temperature for a platinum resistor. The student was asked to design an experiment to measure the temperature of an unknown liquid. More than three out of ten students taking the exam did not attempt this question, and more than one out of eight received no points for their attempt to answer it.

While the question is posed in three parts, readers needed to read sections (a) and (b) together in order to assign points. Many students had difficulty in designing a circuit that used a voltmeter, ammeter, and a power supply to measure resistance. Even students who have had little exposure to laboratory work should be able to construct such a circuit. In part (c) students were asked to discuss one assumption they made in designing their experiment in parts (a) and (b). Any reasonable answer, such as the linearity of the resistor, or the need to extrapolate or interpolate data on the graph, was considered sufficient.

Many students continue to bypass the questions that contain sections that require some familiarity with laboratory technique, data acquisition, and analysis. This suggests that many students do not have much familiarity with laboratory work in the Physics B course.

Question 6

This question was of average difficulty for a 10-point question. Most students who attempted it knew how to apply the ideal gas law in at least one part of the problem. The students did seem to not know how to apply thermodynamic terms appropriately to a thermodynamic cycle.

The question involved the application of the ideal gas laws to a four-part thermodynamic cycle. One difficulty that students had was not knowing that $0^{o}C$ is 273 K. Another was the lack of familiarity with the terms isobaric, isothermal, and adiabatic.

Many students did well on parts (a), (b), and (e), while doing poorly on (c) and (d) owing to this lack of familiarity with thermodynamic terms.

The main problem that students had in (a) was the failure to realize that the pressure of the 2.5 kg mass on the piston must be added to atmospheric pressure to obtain the total pressure in the cylinder. Many students seemed familiar with the ideal gas laws, but evinced little idea of the thermodynamics of ideal gases apart from the hoary chestnut $PV = nRT$.

This problem was easy to grade, but the small pressure change induced by the addition of the 2.5 kg mass led to some problems in part (a). Some students who rounded off the total pressure to two significant figures found no pressure change at all. This error carried through into (b). Future problems should make use of larger changes, at least at the 10% level, to avoid this problem.

Question 7

The last question was of average difficulty. Three out of every ten students who took the exam left this question blank, which speaks more to the length of the exam than to the difficulty of the question. The question began with a simple mass-defect calculation in a nuclear reaction, and then proceeded with extensions and application of that idea through the rest of the problem.

The four-part question began with a calculation of the mass defect of a nuclear fusion reaction. The most common errors here involved arithmetic mistakes, not lack of understanding of the physics involved. Part (b) involved converting this mass defect into energy, which was a straightforward calculation. Few students realized that an order of magnitude answer would suffice for part (c). Part (d) was quite difficult, as five numbers had to be multiplied to obtain the correct answer.

This application of modern physics to a technological problem did not faze many students. This indicates that the relevance of modern physics is being addressed by a substantial number of Physics B teachers. While the large number of blanks is due in large part to the length of the exam, I suspect that a fair number of blanks occurred because the material was not covered.

Physics C: Mechanics

Question 1

This question covered some aspects of graphical analysis in kinematics and dynamics, along with the ability to synthesize information to solve a problem in dynamics. Part (c) of the problem seemed unfamiliar to many students, but otherwise students found this problem easier then average for a Physics C: Mechanics exam.

The problem began with two sections that involved the interpretation of graphs. In part (a), students calculated the average acceleration of a cart undergoing one-dimensional motion by using data from a velocity versus time graph. In part (b), students calculated the change in the momentum of the cart by using data from a force versus time graph. Most students did well on these parts. In part (c), students were asked to find the mass of the cart. This required the students to bring together ideas and information from parts (a) and (b), and was challenging to many students. Part (d), which asked the students to calculate the energy lost in the collision between the force sensor and the cart, caused some problems. Some students claimed that *no* energy was lost, as the kinetic energy became heat. If we had specified the loss of *kinetic energy* this ambiguity could have been avoided.

There are many valid approaches to this problem, and innumerable invalid approaches. This is a good problem to determine some of the misconceptions that students may hold concerning momentum, force, and impulse.

Question 2

This question was slightly more difficult than the first problem on the Physics C: Mechanics exam. This is surprising, as the first two parts seem to be a straightforward application of Newton's law of universal gravitation and circular motion. The third part, which asked students to supply diagrams that were meant to resemble ellipses with Jupiter at one focus of the ellipse, seemed difficult to many students.

The first part of the question asked that students derive a relationship for orbital speed (part (a) i.) and for the orbital period (part (a) ii.) for a satellite in orbit around Jupiter.

Some students did not derive these relations from Newton's laws, as specified, but rather from some variant of Kepler's third law. In the future, requesting that the students derive their relations from $F = ma$ may avoid some of these problems. In part (b), students were asked to calculate the radius of a jovosynchronous (my term) orbit, given the mass of Jupiter and the planet's period of rotation. This "plug-and-chug" part caused the students few problems. In part (c) the students were asked to draw the orbit of the satellite under two sets of conditions. In part (c) i., the satellite's orbital speed was slightly greater than that required for a circular orbit, and in (c) ii., less. The word *slightly* caused some problems, as some students had the satellite leaving Jupiter. The reasoning behind the responses that had the satellite go into a death spiral before crashing into Jupiter was more difficult to understand.

Question 3

The third question was the hardest on the Physics C: Mechanics exam, as is usually the case with problems involving rotational motion. This question involved an application of rotational dynamics, which made it even more daunting.

In part (a), students were asked to find the moment of inertia of a system consisting of two point masses. This caused little difficulty. Part (b) asked students to determine the linear acceleration of a block attached by a string to an object that could rotate in the horizontal plane. This is a standard application of translational and rotational dynamics. Students got through this with varying degrees of success, limited by the time available and the abilities that they possessed. In parts (c) and (d), students were asked to analyze the conversion of gravitational potential energy into rotational and translational kinetic energy. Some students missed the point of the word *total* in (c) and (d).

The explanation parts of the answers to parts (c) and (d) were often not to the point. Students need to realize that brief answers are satisfactory, and expected. Extraneous and incorrect material embedded in a correct explanation can result in the loss of credit, and students should be warned of those consequences.

Physics C: Electricity and Magnetism

Question 1

The first Electricity and Magnetism question was more difficult than similar questions asked on recent Physics C: Electricity and Magnetism exams. The question assessed the students' command of the concepts of electric fields and potentials due to point charges. The final section asked students to find the potential energy of an array of point charges.

The question involved determining the electric fields and potentials that result from a set of four point charges on a line. This distribution was a model of the charge distribution in a thundercloud, and the corresponding image charges induced in the ground. While the intention of supplying a real-life example was laudable, many students were confused by the two drawings supplied with the problem. The charge distribution in the thundercloud, represented by two point charges, was interpreted as being the only charge distribution of consequence. These students then proceeded to do the entire problem with these two charges, rather than the four that comprise the entire model. In part (b) ii., students were asked to compare the magnitude at an off-axis point at ground level to the on-axis point at ground level. Many students interpreted the word *justify* to mean *calculate*. They laboriously calculated the fields at the two points, when a simple verbal explanation was all that was required. Parts (c), (d), and (e) focused more on "plug-and-chug" that had been the case on recent exams.

Despite the nature of the last three sections of the problem, many students had difficulty correctly answering these sections. In particular, most students skipped the calculation of the potential energy of the charge distribution. This is an area that needs some attention. While most students were familiar with the concepts of electric fields and potentials, few had much familiarity with the concept of the potential energy of a charge distribution.

Question 2

The second free-response question was a circuit problem, albeit a slightly unusual one. Those students who recognized that this was an *RC* discharge problem were able to make some progress. Many students had difficulty doing the graphical analysis portion of the problem correctly in part (a) of the question.

The primary difficulty that students had was realizing that this was an *RC* problem. In part (a), students used a voltage versus time graph to determine an *RC* time constant. From this value, and the nominal capacitance value given in the problem, a resistance was then obtained. In part (b), the area of the capacitance plates was calculated through the application of an equation listed on the examination equation sheet, and knowing that the permittivity ε of a dielectric is given by $\varepsilon = \kappa\varepsilon_o$. Here κ is the dielectric constant, and ε_o is the permittivity of the vacuum. Calculation of the resistivity of the dielectric in part (c) was more daunting for many students. In part (d), students were asked to calculate the charge leaving the capacitor in the first 100 minutes. This could be done by integrating the area under the voltage versus time curve numerically or analytically. Students could also use the equation $\Delta Q = C\,\Delta V$, which was somewhat shorter. A variety of inventive but incorrect approaches were also attempted on this final part.

The lower than usual scores on this particular problem can be attributed to two causes. One was the unfamiliar nature of the problem, and the other was the difficulty the students had in interpreting the graph they were given. The students' skills in graphical analysis seem better developed in mechanics than in electricity and magnetism.

Question 3

The third free-response question was of average difficulty for a Physics C: Electricity and Magnetism examination. Questions involving magnetism, and particularly magnetic flux, often present more difficulties for students than electric fields. This question was a straightforward variation on common problems involving magnetic forces between two conductors and the magnetic flux through a closed loop.

The question presented a situation commonly encountered by students in their studies of magnetism and magnetic flux. A current flows through a long cable, creating a magnetic field that exerts a force on another current-carrying conductor suspended above the cable. In part (a), students are asked to find the direction and magnitude of the current in a closed loop, given a battery of emf $\mathcal{E}$ and a wire of resistance R. This part of the question posed little difficulty. In part (b), students were asked in what direction current had to flow in the cable in order to exert an upward force on the current-carrying conductor suspended above it. Many students replied with canned responses such as "parallel currents attract" that did not indicate an understanding of the physical phenomenon. In these responses a short explanation that indicates *why* parallel currents attract is necessary for full credit. The responses must indicate some knowledge of the physical principles involved, in this case the Lorentz force. Part (c) was a straightforward application of the Lorentz force to a current-carrying conductor. Part (d), the only part of any Physics C Electricity and Magnetism question in Section II to require any calculus, was attempted by few students as a result of time constraints. In summary, student performance on this standard problem was about what one would expect, based on previous exams.