The Physics Teacher

PAPERS | FEBRUARY 01 2024

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Phys. Teach. 62, 116–118 (2024)
https://doi.org/10.1119/5.0127554

AAPT
PHYSICS EDUCATION

Version of Record at: https://doi.org/10.1119/5.0127554

COVID-19 Questions for Physics Exams

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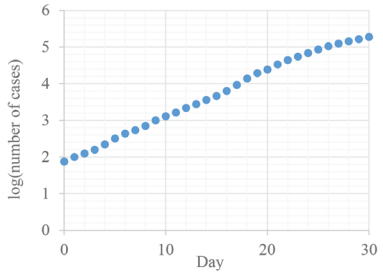
Physics instructors are always looking for questions and activities that both are tractable to students and illuminate real-life applications of physics. This is especially true in Introductory Physics for the Life Sciences (IPLS), where many students enter with the belief that physics is merely a "weed-out" course that has little to do with their majors and career goals.[1] Authentic applications of physics to the life sciences help dispel this myth.

The COVID-19 pandemic provides numerous examples of the relevance of physics to current events and the life sciences. Physics principles are used both to model the spread of the disease and to develop technologies that curb its transmission. Given the disruption COVID-19 has wrought on almost every aspect of life, physics content related to the pandemic inevitably captures students' attention. Few topics are more relevant to their lives, at the time of writing, than COVID-19.

While previous papers report on the effects of COVID-19 on physics instruction,[2] COVID-related curricular materials have not been widely disseminated. This paper looks at how information about the disease can be incorporated into the assessment aspect of a class. Specifically, we share a sample of exam questions we have used to assess IPLS students since the beginning of the COVID-19 pandemic. Since they are exam questions, they are written such that they can be answered by a student in a short period of time as part of a larger timed assessment. Consequently, they are not meant to investigate every possible application of physics to COVID-19. They are also not meant to be collaborative activities that require a substantial amount of time, and potentially interdisciplinary knowledge to solve, although we have used them to assess the knowledge of students who have come through an IPLS sequence using such activities.[3] Instructors looking for inspiration as they develop an activity may find these questions to be a fruitful launching point. These questions can also be used by other instructors on exams or developed into interactive in-class problem-solving activities.[4]

1. On March 1, 2020, there were 75 cases of COVID-19 in the United States. By March 31, the number of cases was 189,967. The graph below shows the logarithm of the number of COVID-19 cases for each day in March. Note: Day 0 is March 1 and day 30 is March 31.



a. [3 pts] The data **between day 0 and day 20** in the above can be modeled by a straight line (note that you can see the "flattening of the curve" after day 20). In the appropriate spaces below, write in the slope and the y-intercept for this line. N represents the number of cases and t is the number of days that have passed since March 1. (Here log = $\log_{10}$.)

$$\log(N) = \_\_\_\_\_\, t + \_\_\_\_\_$$

b. [4 pts] Determine the mathematical equation that relates N and t. Note that this question is asking about N and not $\log(N)$.

Fig. 1. A sample exam question that requires students to determine an exponential function for the number of COVID cases from the data on a semilog graph.

The questions below assess content from three different parts of our IPLS sequence: scaling, diffusion, and electricity. The following sections show the sample exam questions, describe their solutions and their relevance to our IPLS sequence, and discuss students' performance in answering these questions.

Scaling and mathematical modeling

Scaling is the study of how the structures of organisms and their functions change with size. It sits at the interface between biology and physics. Many IPLS courses, including ours, remove traditional content that is less relevant for life science majors, such as Newton's law of gravitation, in order to make room for scaling.[1,3,5] Most scaling relationships take the form of power laws, such as Kleiber's famous discovery that the metabolic rate of mammals scales as their body mass raised to the power of 0.75.[6,7] Many other biological relationships are exponential. Power laws and exponential functions are frequently plotted on log–log and semilog graphs, respectively, where they appear as straight lines. The utility of log–log and semilog plots is twofold: 1) They provide a way to plot data and trends that span many orders of magnitude, and 2) the slopes and y-intercepts of the linear relationships displayed on these graphs facilitate the calculation of coefficients, powers, and other constants that appear in power laws and exponential functions.[7] Consequently, one of our learning goals is for students to translate a straight line on a log–log (semilog) graph into a power law (exponential function) and vice versa. This skill helps students read and interpret graphs in research papers. It also helps them later in the course when issues related to graph interpretation and slopes appear in topics such as kinematics (e.g., determining acceleration from the slope of a velocity vs. time graph) and elasticity (where students learn that Young's modulus is the slope of the stress–strain curve).

Early in the pandemic, the daily number of confirmed COVID cases grew exponentially, until widespread lockdowns began to "flatten the curve." We used publicly available data[8] on the number of COVID cases to produce the graph and exam question shown in Fig. 1. We administered this question to students on their final exam at the end of the spring 2020 semester.

This question explicitly asks students to determine the slope and y-intercept for the linear trend apparent for the first 20 days shown on the graph. Students then had to translate the equation for this line into an exponential function.

Many students did well on this question. The mean for part (a) was 80% (median 100%) with a standard deviation of 31%. Note that students received full credit for any reasonable

calculation of the slope (approximately 0.13) and estimation of the *y*-intercept (approximately 1.8). For part (b), the mean was 70% (median 87.5%), with a standard deviation of 35%. Almost all of the student struggles on this part were due to a lack of good understanding of the algebra of exponents and logarithms.[9] For example, some students stated that, in order to undo the logarithm, one must "raise both sides of the equation to the power of 10," whereas the correct procedure requires one to make both sides of the equation the *power to which* 10 is raised. Other students started with a relationship such as $\log(N) = 0.13t + 1.8$ and then wrote down the incorrect relationship $N = 10^{0.13t} + 1.8$. Perhaps the most common mathematical error students made was claiming that $10^{0.13t+1.8} = 10^{0.13t} + 10^{1.8}$, whereas the correct equation is $10^{0.13t+1.8} = (10^{0.13t})(10^{1.8})$. These issues are addressed in active learning activities in both the lecture and studio portions of our IPLS course, as well as on multiple homework questions, although, as the exam responses show, they persist for some students. We attribute the high scores on this question to the learning that occurred as a result of these activities.

Diffusion

Like scaling, diffusion is a common IPLS topic that many traditional physics courses skip.[1,3,5,10] Our IPLS sequence emphasizes two important points about diffusion. First, it is not a force that pushes particles away from a central point. Instead, diffusion is the aggregate motion of many particles, via random walks, from high to low concentrations. Second, the average (rms) distance traveled by diffusing particles is not a linear function of time. Instead, the rms distance scales as the square root of time, demonstrating that diffusion is a slow process; it takes longer to diffuse a given distance than to travel there in straight-line motion. The relationship between rms distance and time is probed by the question in Fig. 2.

2. [3 pts] Many diseases, including COVID-19, spread because the virus is carried by tiny particles (diameter ~ 10 μm) suspended in air, emitted when people sneeze, cough, exhale, and talk. A recent study found that these suspended particles have an effective diffusion coefficient of 1.6×10^{-3} m^2/s. We have often been advised to stay 6 feet (1.8 m) away from other people in order to reduce the likelihood of contracting COVID-19. For the given diffusion coefficient, how much time would it take for these particles to diffuse this distance? Assume 3D diffusion.

Fig. 2. A sample exam question that asks students to calculate the time required for particles to diffuse a distance of 6 ft.

Figure 2 shows a question that appeared on the final exam of one of our IPLS courses taught during the summer of 2021. The numbers in the problem are taken from a research paper.[11] The question itself is a rather straightforward application of the equation for three-dimensional diffusion relating the rms distance (r_{rms}) to the time t particles require to diffuse that distance: $r_{\text{rms}} = \sqrt{6Dt}$, where D is the diffusion coefficient. Perhaps unsurprisingly, students did very well on this question. The mean was 97% (median 100%) with a standard deviation of 15%. Despite the straightforward nature of the question, it helps students understand how physics explains the common advice we received early in the pandemic to maintain 6 ft of separation from other people. Using the numbers provided in the question, we find that particles need 5.8 min to diffuse this distance (assuming no other aerodynamic mechanisms).

3. [8 pts.] N95 masks keep at least 95% of airborne particles from passing through by two processes: filtering and electrostatic attraction. The electrostatic effect is a result of the plastic fibers in the mask being heated in an external electric field and then cooled to become permanently charged. Water droplets (that could contain a virus) are then attracted to the plastic fibers via the same mechanism that you studied in Studio 7.

a) Water contains equal amounts of positive and negative charge. Explain how the water droplet can experience a net force and be attracted to the charged fiber despite it being electrically neutral.

Suppose a water droplet has landed on a ***negatively charged*** plastic fiber as shown.

b) Draw (or clearly indicate) the direction of the net electric dipole moment in the water droplet due to the presence of the plastic fiber.

c) Suppose that voltmeter leads could be placed on the water droplet as shown by the diamond symbols (this can be done with needle-like attachments). Would the voltmeter read a positive number, negative number, or zero? Explain your reasoning.

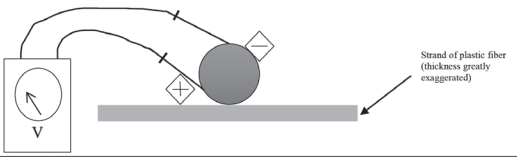


Fig. 3. A sample exam question that probes students' conceptual understanding of the physics of N95 masks.

Electric forces, fields, and potential

Electric forces, fields, and potential are important concepts for both IPLS courses and courses for students majoring in the physical sciences and engineering. In the context of the COVID-19 pandemic, they are critical for understanding how N95 masks work, as explained in a popular science article by Rhett Allain.[12] This article served as the inspiration for the question shown in Fig. 3.

We gave the question in Fig. 3 to our students on a midterm exam during the spring 2022 semester. This question is entirely conceptual in nature, and it was more challenging to students than the questions in Figs. 1 and 2. Students' responses revealed a number of misunderstandings that we plan to address in future revisions of our IPLS curriculum. The primary concern is that 98% of students responding to part (a) of this question were not able to adequately justify *why* there is a net force on the neutral water droplet. Most students (69%) recognized and explained that the charges within the droplet rearranged themselves or polarized so that the side closest to the fiber would have the opposite charge of the fiber and therefore be attracted to it. However, the vast majority ignored the repulsive force of the more distant charges that have the same sign as the fiber. Very few (only 2%) explained that the closer charges experience a stronger attractive force than the more distant charges due to Coulomb's law or the fact that the electric field from the fiber is not uniform but is stronger closer to the fiber. In fact, if the electric field was uniform, the water molecules would experience a torque (polarization) but no force! Since this important point was not recognized by the vast majority of students in our class, we will revise the relevant section of our studio activity on electric forces (using cellophane tape) to help students develop a better understanding of why neutral objects attract both positive and negatively charged strips of tape.

Student performance on part (b) of this question was much better (58% correct), but still not as high as we expected since this was a direct application of a concept that students had seen

multiple times in both lecture and studio. Results for part (c) of this question were mixed since quite a few students misinterpreted the arrow on the voltmeter to be another dipole that altered the electric field. Despite this confusion, 88% of students still applied appropriate reasoning to conclude the correct sign of the voltmeter reading given their understanding of the direction of the electric dipole. Any future use of this question should have a voltmeter that does not include an arrow.

Summary

In this paper, we shared three examples of exam questions that explore the physics behind important aspects of the COVID-19 pandemic. Instructors can use these questions as is or modify them for their courses. Possible modifications include the following:

- In Fig. 1, one can see the "flattening of the curve" that occurred as a result of bans on large gatherings of people. If such bans were not implemented and the trend from the first 20 days continued, how many COVID-19 cases would there have been in the United States by day 30?
- The CDC's recommendation to stay 6 ft away from other people was also accompanied by a 15-min time. Is the time you calculated for the diffusion of particles suspended in air consistent with this time limit?
- Using your knowledge of the electrostatic properties of N95 masks, explain why even an ill-fitting N95 mask can be several times more effective than a well-fitted, but uncharged, mask.

The applications of physics shown in these questions can be appreciated by any student, although they are most relevant to those enrolled in an IPLS course. As society thinks about what life may look like after the pandemic, we must surely agree that the next generation of doctors, scientists, and engineers, who are our current students, should leave our courses with a healthy appreciation for the important role physics plays in managing the current pandemic and future global health crises.

Additional resources

Instructors who are interested in using these exam questions may also want curricula to help them teach the necessary physics to their IPLS students. We have developed over 50 activities, called Physics Activities for the Life Sciences (PALS), that address important physical principles and their applications to the life sciences.[8] These activities are meant to be done collaboratively by small groups of students in a studio or breakout section environment. We have added several of these activities to the Living Physics Portal (www.livingphysicsportal.org), including one on mathematical modeling. Instructors can search for PALS activities on the Living Physics Portal or reach out to any of the authors about activities that are not yet posted on that website (including those on diffusion and electric fields and forces).

Acknowledgments

We acknowledge Gökce Basar, who contributed to the N95 mask question, and Frank Tsui, who contributed to the diffusion and scaling questions.

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