Student Understanding of Ionizing Radiation and Radioactivity

Recognizing the Differences Between Irradiation and Contamination

Edward E. Prather and Randal R. Harrington

Results from research into the teaching and learning of physics have shown that many college students have significant conceptual and reasoning difficulties relating to topics of radioactivity. Interviewing students from three different science backgrounds, the authors identified specific difficulties students had with ionizing radiation and radioactivity and explored students' pre-instruction thoughts on these topics.

Throughout the United States, college students who enroll in introductory geology, biology, chemistry, physics, and astronomy courses receive instruction on the topics of ionizing radiation and radioactivity. Instructors often assume that students already understand these topics and thus they are treated at only a cursory level in college courses. Results from research into the teaching and learning of physics, however, have shown that many college students have significant conceptual and reasoning difficulties with even the most basic introductory concepts (McDermott and Redish 1999). Perhaps the most surprising result is that these student difficulties often remain unchanged even after traditional instruction. These results have led many physics teachers to change their instructional methods to accommodate the needs of their students (Redish and Rigden 1997).

Edward Prather is an assistant staff scientist at the University of Arizona, Steward Observatory, Tucson, AZ 85721; e-mail: eprather@as.arizona.edu. Randal Harrington is a physics teacher, The Harker School, 500 Saratoga Avenue, San Jose, CA 95129; e-mail: randalh@harker.org.

Several articles have been written related to the teaching of radiation and radioactivity that describe novel classroom demonstrations and laboratory activities. These activities are usually intended either to model the radioactive decay process or to help students calculate the half-life of short-lived radioactive isotopes (Austen and Brouwer 1997; Caon 1995; Hoeling and Reed 1999; Kowalski 1981; Mak 1999; McGeachy 1997; Peplow 1999; Ruddick 1995; Russo 1999; Wunderlich 1978). Very little research, however, has been carried out to document the effectiveness of these types of activities on student learning. In addition, little is known about the specific conceptual and reasoning difficulties students have with the topics of ionizing radiation and radioactivity.

The primary goal for the research described in this paper was to identify these difficulties and to provide general insight into how college students think about radiation and radioactivity before receiving explicit instruction on these topics. The students taking part in this investigation were enrolled in introductory physics courses at the University of Maine, including the algebra- and calculus-based courses, as well as a course for nonscience majors. Typical course enrollments were between 80 and 150 students.

Defining Radioactivity

We began our study by conducting informal interviews with individuals and small groups as they performed experiments and answered questions during laboratory activities. Insights gained during these descriptive studies were used to guide the development of protocols used during formal interviews of 10 student volunteers (three algebra students, three calculus students, and four nonscience majors). During formal interviews, students were asked to perform specific tasks or answer conceptual questions designed to provide insight into their beliefs about radiation and radioactivity. Both open-ended and fully scripted protocols were used for these interviews, which lasted from 30 to 45 minutes and were conducted outside of the classroom setting. Each interview was videotaped and analyzed.

We found that, in general, students are conscious of a wide range of both radioactive and nonradioactive sources of radiation. Moreover, students often inappropriately invoke the concept of radioactivity when asked to reason about situations involving non-nuclear forms of radiation such as visible light given off by a light bulb.

Distinguishing Between Irradiation and Contamination

In the next stage of this study we investigated how students reason about situations involving radioactive sources of radiation. Two hundred and seventy-seven students from the same three classes were given a written set of open-response questions involving a situation in which an object is exposed to radiation from a radioactive object, yet does not absorb radioactive material; the object is then removed from the source (figure 1). We chose this situation to learn how well students could perform the subtle reasoning necessary to differentiate this situation from one in which an object becomes a source of radiation (and radioactive) because of the absorption of radioactive material.

These open-response questions were adapted from a set of multiple-choice questions initially used in an investigation conducted by Millar (1994). We chose the open-response format over Millar's multiple-choice format because we wanted to gain more detailed insight into students' beliefs and the reasoning behind their responses (Steinberg and Sabella 1997). Students were instructed to consider the situation shown in figure 1. (Note that the symbols ①, ② and ③ refer to labels in figure 1).

Accompanying this figure was a caption stating that "a juicy strawberry③ was exposed to radiation② from a radioactive source① (Case A) and that the radioactive source was then removed (Case B)." The drawings of the radioactive source① and the emitted radiation② were created to appear similar to drawings that students had made during previous interviews.

All students were then asked the following three questions:

A. Which of the three objects in Case A (the radioactive source①, the radiation②, or the strawberry③) is initially radioactive?
B. Will the strawberry in Case B become a source of radiation?
C. Will the strawberry in Case B become radioactive?

A correct answer for this situation would identify that an object that absorbs radioactive material (i.e., has been contaminated) is now radioactive and consequently emits ionizing radiation. However, an object that is exposed to ionizing radiation (i.e., has been irradiated) does not become radioactive nor does it emit ionizing radiation. Of the three objects (the radioactive source①, the emitted radiation②, and the strawberry③) identified in Case A, only the radioactive source would be radioactive. Furthermore, since the strawberry did not absorb radioactive material, it would not become a new source of radiation or become radioactive.

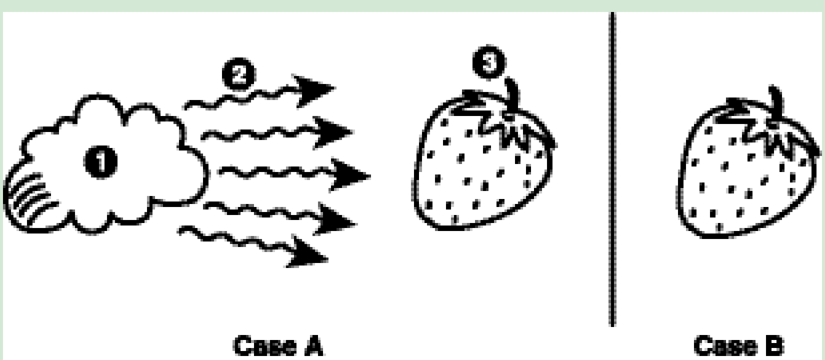
Half of college students in introductory physics believe that an object exposed to radiation becomes radioactive.

Overall, the types of responses provided by students were similar to one another yet distinctively different from the expert view. A summary of responses to the three strawberry questions, which were typical of the questions we asked the students, are provided in tables 1, 2, and 3, respectively.

To get a sense of the overall flavor of the reasoning used by students, we have listed examples of matched responses given by students from all three populations studied (see "Examples of Student Responses to Question on Radioactivity," page 95).

In general we found that, prior to instruction, the majority of students surveyed had a weak understanding of the transport and absorption properties of radiation and radioactivity. Many students provided reasoning consistent with the belief that the exposed strawberry became both a source of radiation and radioactive after being exposed to radiation. Some of these students describe ionizing radiation as having the same properties as radioactive material. These students use the terms "radioactive radiation," "radioactive waves," or "radioactive particles" to describe the emitted radiation. They also believe that radiation is radioactive and that when absorbed, the radiation can cause objects to become radioactive.

Figure 1. ***Drawing of a strawberry③ that is exposed to radiation② from a radioactive source① (Case A). The source is then removed (Case B). Students answered questions about Cases A and B to test their knowledge of irradiation and contamination.***



Some students thought that objects exposed to radiation become radioactive because they have been "excited," "activated," or "made unstable." These students often state that the amount of radiation absorbed or length of exposure influences the magnitude or duration of the induced radioactivity in the exposed object. Even the students who answered correctly that the strawberry would not become a source of radiation (due to its being irradiated) gave reasons that revealed serious conceptual difficulties.

Responses to questions involving irradiation indicated that most students use the terms radiation, radioactive, and radioactivity inappropriately and indiscriminately. The undifferentiated use of these terms made the analysis of student responses difficult. Since it is the differences among these concepts that are at the center of this investigation, we designed another open-response question that required students to reason simultaneously about both irradiation and contamination. We felt that this combined situation would provide students with a clear opportunity to demonstrate if they had a proper understanding of the differences between these concepts.

Two different medical procedures were described in the problem statement that was adopted from another multiple-choice question used by Millar (1994). For the first procedure (Case i) involving irradiation, a strong beam of radiation is directed at a cancer patient's tumor for several minutes. For the second procedure (Case ii) involving contamination, a small amount of radioactive material is injected into a patient's bloodstream and a detector is then used to track how much of the injected radioactive material reaches the patient's lungs. Students were asked if either or both of these medical procedures would cause the patient to become radioactive. A summary of responses to the medical irradiation and contamination question is provided in table 4.

Figure 1. ***Which of the three objects in Case A in figure 1 is radioactive?***

Response Type	Calculus-Physics (N=41)	Algebra-Physics (N=76)	Nonscience (N=160)
Correct (Only the source is radioactive)	44%	26%	15%
Incorrect (The radiation or the strawberry are also radioactive)	56%	74%	81%
Other	0%	0%	4%

Table 2. ***Will the strawberry in Case B in figure 1 become a source of radiation?***

Response Type	Calculus-Physics (N=41)	Algebra-Physics (N=76)	Nonscience (N=160)
Yes, the strawberry is a source of radiation	56%	51%	55%
No, the strawberry is not a source of radiation	39%	46%	39%
Other or No response	5%	3%	6%

Table 3. ***Will the strawberry in Case B in figure 1 become radioactive?***

Response Type	Calculus-Physics (N=41)	Algebra-Physics (N=76)	Nonscience (N=160)
Yes, the strawberry is radioactive	68%	57%	65%
No, the strawberry is not radioactive	27%	41%	29%
Other or No response	5%	2%	6%

Only 24 percent of the students in the calculus-based physics course, 13 percent of the students in the algebra-based physics course, and 13 percent of the nonscience majors responded with correct reasoning that only the second procedure (Case ii) involving contamination would cause the patient to become radioactive. We found that for this context, involving medical irradiation and contamination, some students used distinctly different reasoning from that used in the context of food irradiation. Some students stated that the patient would not become radioactive from the medical procedure Case (i) because the beam of radiation was focused at only a small, localized place, namely the tumor. In another case, students stated that the patient would become radioactive from the medical procedure described for Case (ii) because the radioactive material traveled through the entire body. In both scenarios, the students focused on the physical extent of the interaction between the patient and the absorbed radiation or radioactive material, which can yield the correct answer for the wrong reason.

Another line of reasoning employed by students in the medical context involved restricting the classification of being radioactive only to those objects composed of entirely radioactive material. Since it is rare, if not impossible, to find a material composed entirely of radioactive atoms, this restriction made by students is very subtle.

A third line of reasoning focused on the duration or effectiveness of the interaction between the patient and the radiation or radioactive material. For students reasoning in this way, the outcome of whether the patient becomes radioactive or not depends on (1) how long the radiation or radioactive material was present or (2) how much the patient was altered by the presence of the absorbed radiation or radioactive material.

Table 4. ***Percentages of student responses to four questions concerning radioactive contamination during a medical procedure.***

Response Type	Calculus-Physics (N=17)	Algebra-Physics (N=64)	Nonscience (N=40)
Correct answer with correct reasoning	24%	13%	13%
Correct answer with incorrect reasoning	12%	11%	18%
Incorrect	65%	71%	68%
Neither procedure results in the patient becoming radioactive	24%	44%	25%
Only Case i results in the patient becoming radioactive	0%	8%	10%
Case i and Case ii result in the patient becoming radioactive	41%	23%	33%
Other	0%	2%	1%

Improving Understanding

Although students from different levels of scientific backgrounds were surveyed in this study, their responses were quite similar. Our results suggest that many students believe that an object exposed to radiation will become a source of radiation and/or become radioactive. Overall, most students were unable to differentiate between the concepts of radiation and radioactivity. Furthermore, it is indeed possible for students to provide the correct answer to questions involving radiation and contamination while employing faulty reasoning.

We believe that to account for radioactive phenomenon, one must have a fundamental understanding of how the atom (or atomic nucleus) behaves during the decay process. Either students do not have a clear understanding of the role of atomic nuclei in radioactive processes or they have a basic understanding but do not access this knowledge when asked questions about radioactivity. In subsequent stages of this investigation we focused on how students think about radioactive phenomena in relation to the role of the atom (Prather 2000). Results from this investigation were used to guide the development of instructional strategies at the University of Maine, including interactive lectures, hands-on laboratory-based activities, and tutorial worksheets structured around a directed-inquiry approach (Prather 2000).

Overall, students demonstrated a significant improvement in their conceptual and procedural knowledge about ionizing radiation and radioactivity after instruction using these researched-based teaching materials. In particular, we found that 90 percent of the students from both the algebra-based physics course and the nonscience majors' course were able to reason correctly that an object would not become radioactive after being exposed to the radiation from a radioactive object. Furthermore, 68 percent of the students in the algebra-based course and 84 percent of the students in the nonscience majors' course were able to distinguish correctly between the processes of irradiation and contamination when asked to reason about physical situations involving both processes.

Responses to questions involving irradiation indicated that most students use the terms radiation, radioactive, and radioactivity inappropriately and indiscriminately.

We believe that a combination of these instructional activities and inquiry learning approaches can help reverse the misconception among undergraduates that has led half of college students in introductory physics to state that an object exposed to radiation becomes radioactive.

Acknowledgment

This investigation was conducted at the University of Maine, department of physics and astronomy, by members of the Laboratory for Research in Physics Education (L.R.P.E). The authors extend a special thanks to Donald Mountcastle, David Clark, Steve Kaback, and Andrew Parody for their substantial contributions to this investigation.

References

Austen, D., and W. Brouwer. 1997. Radiation balloons: Experiments on radon concentration in school or homes. *Physics Education* 32(2): 97-100.

Caon, M. 1995. Radioactivity exercises for school: Radioactive decay, the half-life of technetium 99m. *Australian Science Teachers Journal* 41(3): 50-56.

Hoeling, B., D. Reed, and P.B. Siegel. 1999. Going bananas in the radiation laboratory. *American Journal of Physics* 67(5): 440-442.
Kowalski, L. 1981. Simulating radioactive decay with dice. *The Physics Teacher* 19(2): 113.
Mak, S. 1999. Radioactivity experiments for project investigation. *The Physics Teacher* 37(12): 536-539.
McDermott, L.C., and E.F. Redish. 1999. Resource letter: PER-1: Physics Education Research. *American Journal of Physics* 67(9): 757-763.
McGeachy, F. 1998. Radioactive decay: An analog. *The Physics Teacher* 26(l): 28-29.
Millar, R. 1994. School students' understanding of key ideas in radioactivity and ionizing radiation. *Public Understanding of Science* (3):53-30.
Peplow, E.P. 1999. Fiestaware™ radiography. *The Physics Teacher* 37(5): 316-318.
Prather, E.E. 2000. An investigation into what students think and how they learn about ionizing radiation and radioactivity. Ph.D. diss. University of Maine, department of physics.
Redish, E.F., and J.S. Rigden, eds. 1997. The changing role of physics departments in modern universities. Proceedings from the International Conference of Undergraduate Physics Education (ICUPE). American Institute of Physics Conference Proceedings No. 399.
Ruddick, K. 1995. Determination of the half-life of ^{212}Po. *American Journal of Physics* 63(7): 658-660.
Russo, R.N. 1999. La fiesta radioactiva: Distinguishing alpha, beta, and gamma emissions from orange-glazed dinnerware. *Journal of College Science Teaching* 28(5): 348-351.
Steinberg, R.N., and M.S. Sabella. 1997. Performance on multiple-choice diagnostic and complementary exam problems. *Physics Teacher* 35(3): 150-155.
Wunderlich, F.J. 1978. Electronic analog of radioactive decay. *American Journal of Physics* 46(2): 173-177.

Examples of Student Responses to Question on Radioactivity

Calculus-Based Physics Students

Student #1

- Strawberry question A: ① in case A is radioactive because it is sending the radiation waves② and the strawberry is being exposed to them.
- Strawberry question B: The strawberry in Case B is a source of radiation because the radiation waves have upset its nuclear stability.
- Strawberry question C: Yes, since it absorbed radiation waves it's nuclear unstable. It will now give off its own radiation waves.

Student #2

- Strawberry question A: ① because it is the mass losing alpha, beta, and gamma particles. ③ because it has been subjected to the radioactive particles and contains them, and still emits them for a while.
- Strawberry question B: Yes, the radioactive particles have been absorbed into the strawberry and it emits those particles over time.
- Strawberry question C: Yes, because it emits the absorbed particles.

Algebra-Based Physics Students

Student #3

- Strawberry question A: ① because the radiation is emanating from this source. ③ because some of the radiation was transferred to the strawberry.
- Strawberry question B: Yes, since some of the radioactive waves were taken up by the strawberry it is now a source of radioactivity itself and can emit radioactive waves.
- Strawberry question C: Yes, radioactivity was transferred from ① to the strawberry and the strawberry remains radioactive after ① is removed.

Student #4

- Strawberry question A: ① and ② are radioactive. The source is emitting radioactive particles, and the particles travel to ③.
- Strawberry question B: No, the radioactive particles do not stay in the object
- Strawberry question C: No, radiation was absorbed or passed through it. It does not have radioactive potential

Nonscience Majors

Student #5

- Strawberry question A: ①, ②, and ③. ① is the radioactive source so of course it is radioactive. ② is the radiation given off by the source. As it hasn't interacted with anything yet it too is radioactive. I don't think that ③ is as radioactive as ①, but it has absorbed some of its radioactivity.
- Strawberry question B: For a short time, depending on how much radiation it was exposed to, the strawberry will give off the radiation that it absorbed. The radiation it absorbed will radiate until it is gone.
- Strawberry question C: Yes, it must be if it is giving off radiation. But it will only be radioactive for a limited time.

Student #6

- Strawberry question A: All three. ① is giving off radiation. ② are the radioactive particles. ③ is being struck with by radioactive particles.
- Strawberry question B: No, it has no means of giving off radioactive particles
- Strawberry question C: Yes, although it is not a source it contains radioactive particles