**Students Coming to Understand Ionizing Radiation - A Radiation Literacy Challenge**

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## Abstract

Most non-scientists tend to think of radiation as being matter-like "stuff" that is emitted from radioactive objects and causes other objects to become radioactive. This is a significant barrier to radiation literacy. The Inquiry into Radioactivity (IiR) course materials are designed to develop radiation literacy among nonscience majors and to help students understand ionizing radiation as high speed subatomic particles emitted from unstable atomic nuclei. In studying student thinking about radiation and radioactivity, we find over 90% initially subscribe to a "matter-like" view but after eleven weeks of study in IiR, nearly 70% of students adopted a particulate view. This was identified in post-assessement data by examining consistency of multiple student responses with a particulate model. We believe that this transformation in thinking is comparable in difficulty to other major conceptual changes in physics. The Inquiry into Radioactivity project is supported by NSF DUE grant 0942699. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation or of Black Hills State University.

## Introduction

Ionizing radiation is becoming more prevalent and important in modern life. Gamma scintigraphy and X-ray CT scans are increasingly used in medicine, industrial uses of radiation are proliferating, and the recent Fukushima disaster raised the visibility of radioactive hazards. A society that uses nuclear technology ought to be radiation literate. However the topics of radioactivity and ionizing radiation tend to be taught briefly, if at all, in science courses for non-scientists, and there is little evidence of understanding of radiation by these students. The Inquiry into Radioactivity (IiR) Project is developing and testing the needed tools and techniques to develop radiation literacy among non-science college or high school students. A radiation literate person would understand what radiation is, where it comes from, and how it can do harm.

In other words, a radiation literate person would:

- Think of ionizing radiation as tiny particles radiating at high speed from a source,
- Identify sources of ionizing radiation as unstable atomic nuclei and special devices such as X-ray machines, and
- Understand and be able to explain the effect of ionizing on molecules, cells, and ultimately on people, and have very general ideas about how to mitigate harm from radiation and how medicine uses radiation for diagnosis and cancer treatment.

This paper reports the findings of a study on student understanding of the fundamental properties of ionizing radiation. This topic is important to science education researchers because if radiation is to be taught effectively, the learning difficulties must be understood along with techniques for overcoming these difficulties.

Most people have ideas about radiation that conflict with the scientifically accepted view. European researchers found that students (and the general public) do not correctly view ionizing radiation as high speed particles emitted from radioactive atomic nuclei[1,2]. Instead, most view it as "matter-like". British researchers Millar and Gill[3] described typical ideas about radiation:

> *". . . many students have an undifferentiated concept of 'radiation/radioactive material' which they see as somehow spreading out from a source and affecting other objects in the vicinity. Its effect becomes less at greater distances. The spreading of this 'entity' is associated with danger and harm to living things. If it is 'absorbed' by an object, it may be re-emitted later."*

In other words, most people - including college students - tend to think of radiation as "bad stuff" that "contaminates things" (like dirt or germs) and they do not distinguish radiation - the emitted phenomenon - from radioactivity which is the condition of emitting radiation. This general set of ideas also prevails in the US among all levels of introductory physics students[4], making it unlikely that students can meaningfully reason about radiation until they develop a view that is more consistent with the particle model. This is called the “undifferentiated view” because a person thinking this way does not differentiate radiation from radioactivity.

Based on Millar & Gill's characterization above, this research formalized the "undifferentiated view" as being composed of three facets: radiation is matter-like, there is no difference between radiation and radioactive, and radiation can be transferred to other objects making them radioactive. While these three facets are closely linked, students sometimes express one or the other in different contexts. Distinguishing between these facets enables investigators to more easily characterize a student's state of differentiation and to determine whether students tend to change their thinking one facet at a time or all at once. Students who are "differentiated" instead refer to radiation as particles in motion that do not contaminate other objects, and these students distinguish between radiation and radioactivity. While radiation is constituted by particles of matter, its crucial characteristic is their motion.

**Setting & Methods**

The IiR project is being developed in a Survey of Physics course at a small, public Midwestern college. Students in this course are roughly representative of nonscience majors in other rural moderate-income populations.

Data was collected from student work, journal entries, homework assignments, in-class observations, conversations, end of unit interviews, and video recordings. Multiple data sources were used for triangulation when possible. Data in this study came from 36 students in two sections of Survey of Physics at the beginning and end of the Fall 2011 semester.

We developed assessments for use early in the unit and late in the unit. These addressed the issues of differentiation and provided multiple opportunities for student responses.

Student initial ideas were characterized by the "Radiation Conceptual Diagnostic" which asks various questions about radioactive objects, radiation, contamination, and includes questions about electromagnetic devices.. For this research, the Radiation Conceptual Diagnostic was mostly freeresponse questions, but latest version of this instrument, in Appendix 1, uses a multiple choice format.

The "strawberry question" used by Prather and Harrington (2001) was very useful:

*A radioactive source is placed next to a strawberry. The diagram shows the source, the radiation, and the strawberry.*

*a) Which of the three objects is/are radioactive?*

*b) The radioactive source is removed. Did the strawberry become radioactive? Explain what it takes for the strawberry to become radioactive - or not.*

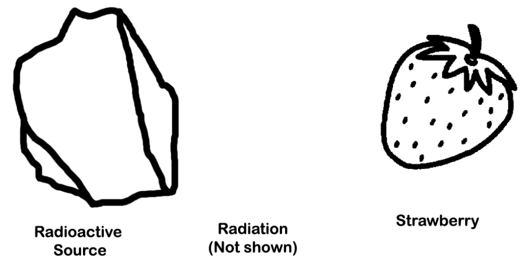


**Fig. 1. The Strawberry Question**

Student thinking was inferred based on their answers to questions such as this. For example, some students would write answers such as "The source, the radiation, and the strawberry are all radioactive". This allows the inferences that the student is thinking that radiation contaminates other object, and has not distinguished radiation from radioactivity.

Some categorizations were based on students' choices of words - for example, if a student said "radiation is ON the strawberry" we inferred that the student was thinking of radiation as a material, and probably was thinking of contamination. Students with consistent or nearly consistent answers across numerous responses could readily be characterized as differentiated or not differentiated for each facet. Other students with mixed responses were characterized as "partly differentiated" within a given facet.

Student thinking about radiation at the end of the unit was assessed using responses on homework, and selected questions from the midterm exam. Exam questions were different from those on the Radiation Conceptual Diagnostic pretest. Two examples are:

> *Suppose we stuck all of our plastic radioactive disks on an apple for the month of September while it was hanging on the tree. Would the apple become radioactive? Explain.*

(The apple question was helpful for identifying student thinking about contamination).

> *In April 2011 Japanese health authorities announced that produce from farms near the Fukushima nuclear reactor - including some apples - was radioactive. Explain how this can happen.*

(The Japanese produce question gave information about student thinking about radiation as having material-like characteristics, and about contamination).

Eleven exam questions were used to characterize student thinking in each facet. When the majority of responses were consistent with the differentiated or undifferentiated views, the student's thinking was coded accordingly. Students with more than two responses consistent with both views were coded as "mixed."

**Initial Results: the undifferentiated view**

At the beginning of the course, 81% of students were clearly undifferentiated in all 3 facets and the remaining students were categorized as "mixed" and a very few as differentiated. The undifferentiated views with sample statements from the three categories are characterized below:

*Radiation as a material*

Student statements about radiation traveling or being stored implied that they were using a material-like idea to explain radiation. For example, when asked whether a radioactive source would make a strawberry or a nuclear plant worker radioactive, some student responses were quite clear about radiation having matter-like characteristics:

> "[The strawberry is radioactive because] it stores the radiation".
>
> "[Workers exposed to radiation] should not be separated from other patients because the radioactivity is contained in their bodies only".

*Radiation transfers*

Students expected radioactive objects to cause nearby objects to become radioactive via some kind of contamination. This contamination often shared characteristics with something like dirt or an infection but was not quite the same.

> "[The strawberry] isn't radioactive because the radiation didn't have time to infect it".
>
> "Yes, I believe [a worker exposed to radiation] should be [separated from other patients] because they could transfer the radiation. (I know this because I have seen it in quite a few movies)".
>
> "I think they should have their legs amputated so the radiation doesn't spread to the rest of their bodies...then the feet can be properly disposed of and you wouldn't have to worry about infecting other patients".
>
> "[The strawberry became a source of radiation] because the waves reached the strawberry".

Note: Students frequently talked about radiation as waves. They would claim that radiation is made of waves or comes in wave form, even though they did not apparently understand the basic characteristics of waves.

*Radiation is radioactive*

Many students did not distinguish between the source of the radiation and the radiation itself. Students use the words “radiation” and “radioactive” apparently interchangeably. One of the strawberry questions asked which of the three objects (source, radiation, strawberry) was radioactive and 50% of students listed “radiation” as radioactive.

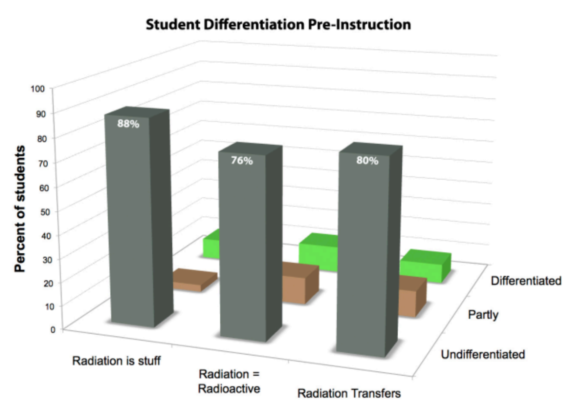


Figure 2: Student differentiation in the three facets before instruction

Figure 2 shows overall initial findings: 88% of students were undifferentiated in their view of radiation as a material or “bad stuff”, 76% were undifferentiated in their definition of radiation versus radioactivity, and 80%

were undifferentiated in their view of radiation as a transferrable contamination.

## Final Results

Shown in Figure 3, by the end of the investigation at the end of the unit most students had become differentiated. The number of partially differentiated students also increased. Responses from these "partially differentiated" students were sometimes consistent with the particle view and sometimes not. Partially differentiated students appeared to be in transition to the fully differentiated view.

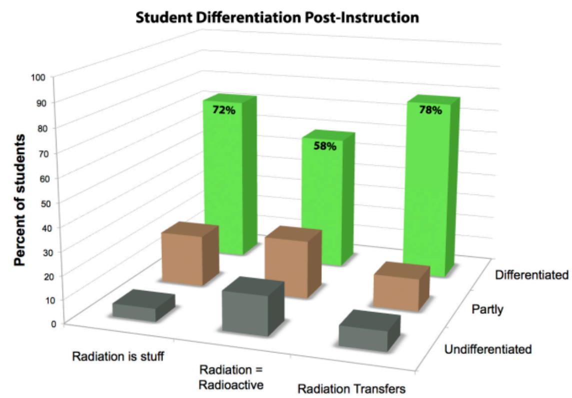


Figure 3: Percentage of student differentiation in the three facets post-instruction

## Discussion

An overall "differentiation" indicator was made by adding scores of the three different facets with full differentiation only when a student was fully differentiated on all three facets. The pre-post results on this overall indicator are shown in Figure 4. Effectively, 64% of the students shifted from undifferentiated to fully differentiated, and another 24% shifted from undifferentiated to partly differentiated.

The IiR materials clearly helped students reconsider and replace their undifferentiated views with more sophisticated particle- like views of radiation. Classroom observations and later research suggest that student thinking changed gradually as students developed detailed understandings of radiation as subatomic particles moving at high speeds, of radiation being emitted from certain unstable nuclei, and of radiation ionizing matter it encounters. Details of this picture emerged for students through weeks of sequenced investigations.

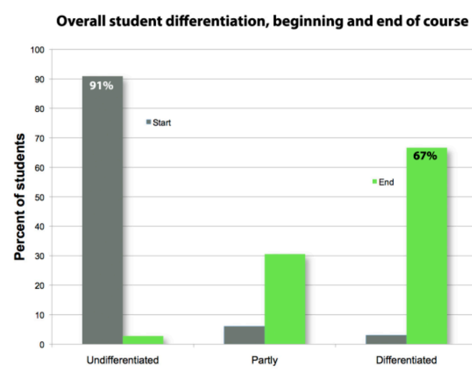


Figure 4: Percentage of overall student differentiation pre/post

For most students the three facets of the undifferentiated view were connected - more often than not, students were fully differentiated on all three facets at the end. However, 64% of partially differentiated students were fully differentiated on one or two of the facets but had not differentiated the remaining facet(s) at the end of the course. Therefore the three facets are somewhat distinct from each other.

The differentiation process took place gradually over more than 30 hours of instruction and apparently was not easy for most students. This is because students had to construct largely new understandings of radiation, abandon old ideas, and come to view radiation and radioactivity as different things. According to Dykstra[11], concept differentiation is a type of conceptual change. Making a conceptual change is typically difficult and sometimes painful for the learner because the change requires seeing the world in a new and initially unfamiliar way. It requires that some familiar ideas must be abandoned while other ideas must be transformed and used in new and different ways. Common hallmarks of conceptual changes include:

- making an ontological shift from the old way to the new way of thinking,
- student confusion and frustration while making the shift,
- tendency to revert to the old idea even after it has been shown to be untenable.

All three of these characteristics were observed in the radiation classroom.

The undifferentiated view interferes with the scientifically accepted idea that radiation only harms tissues but does not contaminate, colonize or propagate inside other objects. Thus, those students who had not differentiated had additional difficulties with studying the health effects of radiation, and sometimes resorted to rote memorization instead of reasoning on tasks and assessments.

In a separate research project based on the same course and data, Hafele and Johnson[6] found that students who differentiated radiation from radioactivity tended to be much more successful with understanding ionizing by radiation. Ionizing scores and differentiation scores were calculated for each student. The correlation between the two of 0.53 for a linear regression fit was significant at a p value far below 0.05. Ionization by ionizing radiation is the key phenomenon that must be understood to make sense of the effects of radiation. Those students who did not differentiate were much less likely to understand the ionization process. These difficulties persisted for undifferentiated students despite multiple explicit experiences with those phenomena in the course including specially designed simulators that showed alpha, beta, and gamma radiation particles removing electrons from molecules.

**Conclusions**

This research has shown that - using the IiR materials - two thirds of a group of non-science majors came to differentiate radiation meaningfully, eventually viewing ionizing radiation as subatomic particles moving at high speed instead of as "bad stuff that causes contamination". This is baseline data that can be used for comparison to other radiation literacy education efforts. Moreover, Hafele's results highlight the stakes in students achieving this basic understanding - that developing a meaningful understanding of the interaction of ionizing radiation with matter is strongly correlated with developing a viable particle view of radiation in the first place. Differentiation may be a prerequisite for understanding ionization by radiation.

Observations in the classroom suggest, however, that understanding of ionizing radiation is rendered significantly more difficult than one would hope by the necessity of constructing substantially new ideas, and by conflicts with students' initial ideas about radiation. Student thinking about contamination persisted long after experiments and simulations showed that ionizing radiation does not cause contamination. Thus differentiating radiation from radioactivity is not straightforward for many students.

These times call out for widespread radiation literacy. Meeting this challenge unfortunately seems to require carefully designed learning activities at the level of intensity and duration of the Inquiry into Radioactivity course. More information about the IiR materials is available at: http://www.camse.org/radiation

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**Appendix 1:**
**Radiation Conceptual Diagnostic**

**1) Draw a picture** of a situation in which you *expect to encounter radiation* and *what the radiation might look like* if you could see it.
***Please describe in words what you have drawn!***

**2)** If we say something is radioactive, what might that mean? *Check **all** that apply*:

| | |
|---|---|
| ___ It's dangerous | ___ It's made from dangerous chemicals |
| ___ It emits radiation. | ___ It's electrical |
| ___ It reacts or will explode | ___ It's manmade |
| ___ It produces waves | ___ It's naturally occurring |
| ___ It must have been exposed to radiation | ___ It will make other things radioactive as well. |

**3)** A geiger counter is a handheld device that detects radiation from nuclear waste and other radioactive sources. Officials in Japan used geiger counters to monitor radiation levels after the Fukushima nuclear reactors exploded in 2011. When held near a radioactive object, a geiger counter gives a clear indication of radiation. Which of the following objects might make a geiger counter register?
*Check **all** that apply.*

| | | |
|---|---|---|
| ___ Sunlight | ___ Person with a pacemaker | ___ NASCAR engine revving fast |
| ___ Computer | ___ Microwave oven | ___ Lead-based paint |
| ___ College student | ___ Food taken out of microwave | ___ Electrical outlet in the wall |
| ___ Cell phone | ___ X-ray machine | ___ Uranium ore |
| ___ Strong chemical herbicide | ___ Mercury thermometer | ___ Can of Chlorox wipes |
| ___ Drain cleaner chemicals | ___ Moonlight | ___ Table under an x-ray machine |

**4)** If you put a sealed container of radioactive waste somewhere ("sealed" means no fluids can get out), is it safe to be near the drum? (*select **one** best answer*)


a. Yes, the drum is sealed so radiation can't leak out.
b. Yes, as long as radiation fumes or chemicals are sealed in and do not cause an explosion then there is no danger from radiation.
c. No, radiation waves can still go though the drum even though the contents inside can't escape.
d. No, radiation particles can still go though the drum even though the contents inside can't escape.
e. No, if the container becomes radioactive from exposure then it is not safe.
f. Other: *please explain*:

**5)** Is radiation all the same type, or might there be more than one kind? (*select **one** best answer*)

a. There are different levels of intensity but only one kind.

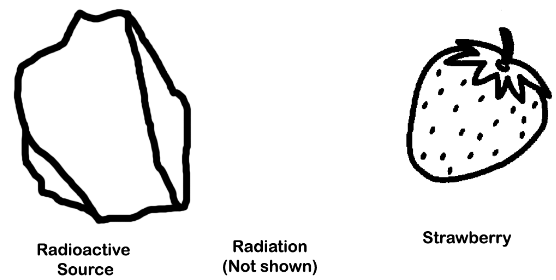
b. There is one kind of radiation but it comes from different sources.

c. There are different kinds - based on the wavelength of the radiation only.

d. There are different kinds - some are more like particles and some are more like waves.

e. There are different kinds - they come in liquid, gas, and solid forms.

A radioactive source is placed next to a strawberry as shown. (*select **one** best answer*)




**6)** Which of the three objects is/are radioactive?

a. The radioactive source, the radiation, and the strawberry are all radioactive.

b. The radioactive source and the radiation are radioactive.

c. The radioactive source and the strawberry are radioactive.

d. The radioactive source only is radioactive.

**7)** The radioactive source is removed. Did the strawberry become radioactive?

a. Yes, the strawberry is radioactive because it was exposed to radiation.

b. Yes, if the strawberry came into contact with the radioactive source, the radiation would stay on it.

c. Yes, because radiation would infect objects near the source, causing them to become radioactive.

d. Not unless the strawberry was exposed to radiation for a prolonged period of time and at high levels.

e. No, exposure to radiation would not make the strawberry radioactive.

**8**) During the emergency at the Fukushima power plant, each reactor worker wore a thin plastic suit that kept dust off. Would this suit protect a worker from radiation?

a. Yes, as long as the suit is not torn or damaged then the radiation cannot come in contact with the worker.

b. Yes, the suit would keep the radioactive dust off the worker but he is still exposed because some types of radiation can go through the suit.

c. No, because the waves can penetrate through the thin suit exposing him to radiation.

d. No, because the radioactive dust would make the suit radioactive, causing the worker harm.

e. No, because the radiation would burn or eat through the plastic.

f. Other: *please explain*:

**9)** If a reactor worker is exposed to a large dose of radiation (while wearing the plastic suit) can he help himself by removing the suit in a clean area and then washing thoroughly? (*select **one** best answer*)

a. Yes, if done in time washing may remove the radiation from the workers skin.
b. Yes, there could be treatments like drugs or chemicals that could counteract radioactivity.
c. No, because the waves that penetrated the suit have already done damage to the workers body.
d. No, it is too late to wash. The radiation has already seeped into the skin.
e. No, because the effects of radiation cannot be washed away and the damage is already done.
f. No, nothing can be done for the worker; he needs to be quarantined to protect others from radiation.

**10)** Suppose the worker takes off his suit. Would a Geiger counter (a device that measures radiation) register any extra radiation coming from the worker?

a. Yes, the worker has been exposed to radiation
b. It depends on whether some of the radiation seeped through the suit and got on the worker.
c. It depends on the strength of the radioactivity, how long he was exposed, or how effective the suit was.
d. No, the radiation passed through the worker or did damage but it didn't make him radioactive.

**11)** Suppose the worker was exposed to a large amount of radiation while wearing the suit but his wife wants to visit him in the hospital if she can. How close can she get to her husband without endangering herself?

a. Be in the same building as her husband
b. Be in the same room with her husband but separated by a thick leaded glass window
c. Be in the same room with her husband but not touching
d. Hold her husband's hand but not kiss him for fear of contracting radiation from him
e. He's not dangerous to her, she doesn't have to worry about her health.

**12)** While working at the stricken Fukushima power plant, a worker received a large dose of radiation even though the reactor was not running. He was taken to a hospital to be monitored for health risks. Do you suppose the worker should be separated from other patients because of radiation risks to others?

__ a. Yes, the radiation he has absorbed could be contagious so the nurses need to wear gloves and handle his body fluids with care.
__ b. It depends on how long he was exposed
__ c. It depends on how strong the radiation was
__ d. It depends on which type of radiation it was
__ e. Choices b, c and d together
__ f. Choices a, b, c, and d together
__ g. No: Even though he was exposed to radiation he isn't emitting any

**13)** Suppose the Fukushima worker experienced a strong dose of radiation to only one of his feet. The rest of his body did not receive a large dose. What should be done about the worker's foot? (*select **one***)

a. Radiation will spread throughout the victim's body so the foot may have to be amputated.
b. They should try to wash the radiation off so it won't harm other people.
c. The foot should be sealed off with a lead boot to protect the hospital workers.
d. The foot will emit radiation but not enough to be hazardous.
e. The foot is not a risk to anyone, but it could be damaged.

**14)** A particular chemical storeroom contains many different chemicals but none of them are radioactive. Do you suppose it might be possible to mix some of those chemicals in such a way that the result would be radioactive? Explain.

**15)** We have heard that cell phones produce radiation. After a cell phone has been in use for many years, might some of its component parts (the antenna or the battery, for example) still emit radiation after the phone is taken apart? Explain.