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Identifying & Resolving Problematic Student Thinking About Ionizing Radiation

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Abstract

We are developing an inquiry-based radiation curriculum for teaching radiation literacy at the high school and college levels. We have found that students' initial ideas about radiation are problematic for comprehending the characteristics and effects of radiation. For example, students initially do not distinguish between radiation and the radioactive source. In an earlier study, Eijkelhof[1] clearly identified undifferentiated radiation concepts among Dutch high school students. The undifferentiated view is that radiation is "bad stuff", that there is no difference between radiation and radioactivity, and that radiation causes contamination.

The goal of the radiation materials is for students to develop the more sophisticated view of radiation as high-speed, subatomic particles. Such a view distinguishes between radiation and radioactive materials and enables thinking about mechanisms of radiation emission and interaction with matter. Problems arise as students develop the subatomic particle view - for example, many try to hang on to the contamination idea of radiation.

This study builds on the research of Eijkelhof to identify and characterize students' initial ideas about radiation in terms of Eijkelhoff's undifferentiated radiation concept. We identify the avenues by which the majority of the students in the trial course developed more sophisticated ways of thinking, characterize the learning gains, and determine if a conceptual change was in fact necessary to develop these new models of thinking. Using qualitative methods, we have inferred student thinking from conversations, observations, video recordings, interviews, and class work in order to determine their models of thinking from beginning to end. This research is part of the Radiation By Inquiry project 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.

Keywords: Learning, Education, Radiation

Introduction

The Radiation By Inquiry (RBI) project is developing guided-inquiry based course materials for teaching radioactivity to nonscience majors. Students are provided with supportive and carefully sequenced materials such as hands-on labs and computer simulations to build their understanding of the scientific view of the radiation process. We are teaching radiation to nonscience majors for radiation literacy in a highly interactive manner.

Through this process we're investigating learning in the classroom to determine where these students are at in their understanding of the scientific view of radiation. We begin by gathering information about where the students are at in their thinking and understanding of radiation before any classroom instruction on the matter. This initial data gives us our basis for understanding where the students are at in their comprehension of the radioactive process. By then incorporating the RBI materials throughout the course, students can build and even change their original thinking. However, as a result of our investigation, we have been finding some difficulties in the students' thinking and understanding of the scientific view of radiation. Even students with more scientific background and knowledge have been noted as having a mixed initial understanding of radiation.

Because of this notable difficulty in our students' understanding, we're developing new course materials that are intended to help people develop conceptual understanding of radiation.

The Problem With Learning About Radiation

Ionizing radiation is high speed particles emitted from radioactive atoms. For example, beta radiation consists of electrons emitted at high speeds from atomic nuclei that have undergone a particular transformation. This image from the Atom Builder simulator used in the Radiation by Inquiry materials shows a beta (electron) in the circle to the right and a nitrogen-14 atom that results from carbon-14 emitting the beta shown.

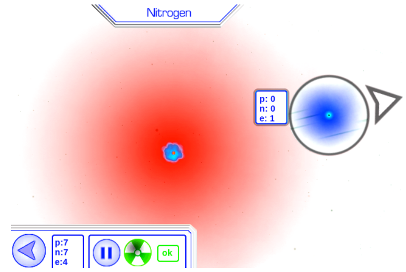

Figure 1: Scientific model of beta radiation

The beta can ionize other atoms that it encounters as it travels through space.

The above description of beta radiation is quite different from how most people initially tend to view ionizing radiation. Unfortunately, when people first think about radiation, most conceptualize it as "matter" rather than as a process of emission of high speed particles and they do not distinguish between radiation itself and the condition of being radioactive.

German researchers found this as early as 1975[2]. Described in Eijkelhof [1], Riesch and Westphal noted that students "seem to confuse ideas about the transport of radioactive sources with those about the propagation of radiation: everything is brought under the name of 'radiation'". Dutch researcher H.M.C Eijkelhof noted similar issues with both journalists and Dutch science students in 1990. In news reports on the Chernobyl disaster and in a questionnaire given to Dutch students of age 15, the researchers found many cases of "the undifferentiated radiation/radioactivity/radioactive material concept". The implication is that many journalists did not understand radioactivity much better than middle school age Dutch children!

In 1996 Millar and Gill[3] summarized the undifferentiated view more concisely with the following characterization:

> *". . . 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 later work, Prather and Harrington[4] found similar views among students in calculus-based, algebra-based, and conceptual introductory physics courses. Prather investigated the undifferentiated view with the "strawberry question"--a strawberry is placed near a radioactive source. Students were asked what was radioactive, and whether the strawberry would be radioactive when the source was removed. Among Prather and Harrington's results, 68% of calculus-based physics students before instruction on radiation thought the strawberry would remain radioactive when the source was removed. Also, 57% of the algebra-based students and 65% of nonscience majors believed the same. Thus the level of physics course did not matter - before instruction, all students seem to think along similar lines.

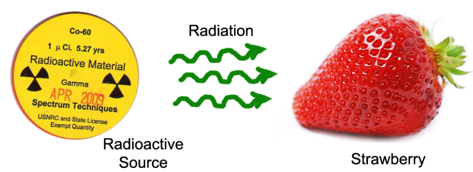

Figure 2: Prather's strawberry question.

The problem of differentiating radiation from radioactivity is a key consideration in the teaching of radioactivity. Physics and other courses often present the scientific view of radiation briefly but in fully differentiated form. We now know that students do not simply absorb information but they interpret everything they are taught in light of their existing knowledge[5]. If a student is thinking of radiation as a material, he or she would have difficulty coming to grips with radiation as tiny high speed particles emanating from radioactive objects. The two ideas represent different ontological categories – in the undifferentiated view, radiation is "bad stuff" similar to toxic chemicals whereas the scientific view presents radiation as a process of particles being emitted and traveling through mostly empty space. In order to adopt the scientific view, students have to shift the ontological category of radiation in their thinking. What does it take for students to make this shift? How often and how readily is it accomplished? Are there techniques for helping students differentiate radiation from radioactivity? These questions have yet to be answered.

Our contribution begins with formalizing the undifferentiated view as being composed of three facets: radiation is material, 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, they are sometimes expressed separately in different contexts. Distinguishing between these facets enables us to more easily characterize a student's state of differentiation. Also, we are interested to find out whether students tend to change their thinking one facet at a time or all at once.

Our research questions:

- Can we use the three facets to identify the undifferentiated and differentiated views in the classroom?
- How do we characterize student views of radiation early and late in their study of radiation?
- What can we say about the process of becoming differentiated using the RBI materials, if it happens?

One remaining issue is the question of conceptual change. Physics education research has identified numerous problematic ways of thinking that students must change in order to understand the physics world conceptually. Learning these particular ideas require students to undergo conceptual changes[6]. Most problematic conceptions in physics involve well established preconceived notions - for example, many students relate the velocity of an object to the forces acting on an object, rather than correctly associating forces with the object's acceleration. The "force equals velocity" idea is the result of years of experience with moving objects around in the world and is regarded as a strongly held alternate conception[7].

In comparison, ideas about radioactivity and radiation are not based in direct experience but on rare and limited discourses in everyday life, and on movies and games. Is the undifferentiated view deep-seated and difficult to change? Does it require a conceptual change or do students readily change their thinking to align more closely with the accepted scientific view of ionizing radiation and radioactive sources? Whether understanding the scientifically accepted view of radiation requires a conceptual change or not has not been established by research. This paper will not attempt to fully answer that question but we hope some of our findings will point to some indicators about it.

Setting & Methods

The project is located in a Survey of Physics course at a small, Midwestern college. This course has roughly equal numbers of each college grade level with a maximum of 24 students per class. Most of these students are apprehensive about science, which is why they have elected to take Survey of Physics which offers the least amount of math work possible in a physics class.

Data for this project 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. From these sources we have been able to collect pertinent data and infer student thinking. We collected data from 35 students in two sections of Survey of Physics 101 throughout the progression of the Fall 2012 semester. Our analyses sought both to understand student thinking (via qualitative methods) and to assess differentiation at the classroom level using quantitative methods.

We constructed two assessment items for use early in the unit and late in the unit. Both addressed the issues of differentiation and provided multiple opportunities for student responses. The assessment of initial thinking was based on Prather and Harrington's strawberry question described above, and it contained additional questions as well.

The post assessment consisted of three specific exam questions which addressed the same conceptual issues but in greater depth and in different contexts. We evaluated student thinking by looking for student responses that corresponded to each of the three facets: radiation is material, there is no difference between radiation and radioactive, and radiation can be transferred to other objects making them radioactive. Some students were consistent in multiple answers and could readily be characterized as differentiated or not differentiated for each facet. Other students responded sometimes in alignment with the undifferentiated view and sometimes with the differentiated view - these we characterized as "partly differentiated" within a given facet.

Teaching about radiation

The course materials are specially designed to support the development of meaningful understandings of radiation and radioactivity. They are being developed in a continuing cycle of classroom trial testing, assessment, and further development. In the classroom, students perform investigations in small groups and discuss key questions in guided inquiry group work. The students and the class as a whole are the primary source of ideas and explanations – which places a higher burden on sense-making by students. Some of the activities designed to help students differentiate radiation from radioactivity included:

- Students interpreted Geiger counter clicks as "events" or "quanta" rather than waves or "material".

- The course introduced Millar’s “source - radiation - detector” model to help students distinguish between the behavior of radiation and the condition of being radioactive.
- Groups observed and interpreted radiation from unstable atoms in the Atom Builder computer simulator.
- Students irradiated objects and later tested them, finding no contamination.
- Groups developed mechanistic models for radiation damage to materials using the Atom Invaders and Tracks simulators.
- Students also considered the special conditions for radioactive nuclei and the observed (simulated) effects of radiation on matter – they repeatedly observed that radiation does not affect nuclei.

More information about the RBI materials is available at: http://www.camse.org/radiation

Results

The undifferentiated view

At the beginning of the course, as determined by pre-instruction data, the majority of students were clearly undifferentiated. Their views on the three categories are characterized below:

Radiation is a material

Students described radiation as toxic chemicals or reasoned about radiation as if it is a material. For example, students were asked Prather and Harrington’s strawberry question. Some student responses were quite clear about radiation being a material:

"[The strawberry is radioactive because] it stores the radiation".

"The strawberry is not radioactive because the radiation didn't bond with it".

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

The third statement is from a scenario in which two workers at a nuclear power plant step in radioactive water but are washed and then taken to the hospital. The students are asked to explain if the workers should be separated from other patients due to health risks.

Much of the time the "radiation as material" facet was not expressed directly. However, student reasoning about radiation traveling or being stored implied to us that they were still using a material-like idea to explain radiation. In fact, early in the course, many students referred to radiation as waves. However, due possibly to their low level of understanding of what a wave is, students who referred to waves also sometimes used the "radiation as material" idea even though these two views are viewed as inconsistent by scientists.

Radiation transfers

Students expect radioactive objects to cause nearby objects to become radioactive via some kind of contamination.

"[The strawberry] isn't radioactive because the radiation didn't have time to infect it".

"[The strawberry became a source of radiation] because the waves reached the strawberry".

In one class discussion, 42% of the students agreed that a bicycle leaning against a drum of radioactive waste would become radioactive itself while another 42% thought it would not become radioactive. The remaining students did not take a position on the issue.

Students thought in different ways about radiation transferring to other objects. Some thought that radiation is like a material. We call this the “Dirt Theory” of radiation.

Figure 3: The Dirt Theory of Radiation

In this view many students seemed to be thinking of radiation similarly to dirt which can be transferred under certain circumstances. The dirt theory is our sense of how students are reasoning.

Example of a student reasoning similarly to the dirt theory:

"Yes, I believe they 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)".

The second transfer idea is that radiation behaves like an infection:

"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".

Some transfer views couldn't be categorized as dirt theory or germ theory:

"If the workers were exposed [to a puddle of radioactive water] for only a moment, the danger of radioactivity is most likely low and harmless. If they were exposed for ten minutes or more the chances of contamination are much higher".

Radiation is radioactive

In this view, students do 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.

Student quote: "The radiation is radioactive".

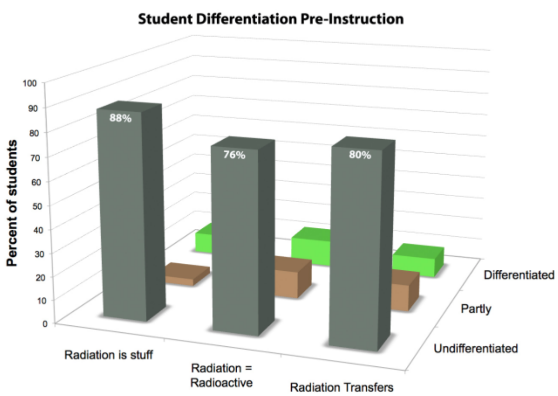

Figure 4: Percentage of student differentiation in the three facets pre-instruction

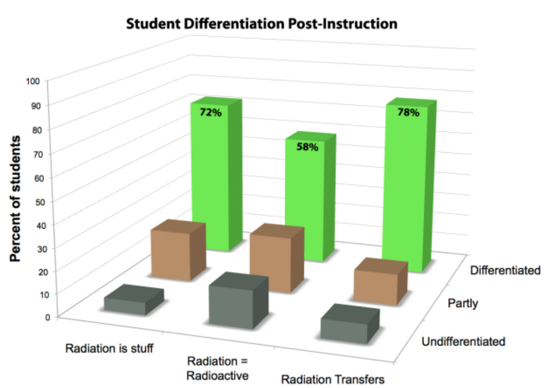

Figure 5: Percentage of student differentiation in the three facets post-instruction

Measuring differentiation

As presented in Figure 4, initial coursework and data collected showed that 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. Students that had an understanding of radiation that fell between the two views, partly differentiated, were small in number with only 3%, 12% and 9% respectively. The number of students that were fully differentiated at this point in our classroom was small as well with 9% in radiation as a material, 12% in radiation compared to radioactivity, and 9% in radiation as a contaminant.

Shown in Figure 5, by the end of our investigation at the end of our unit 72% of students had become differentiated in their views on radiation as a material, 58% had become differentiated in radiation compared to radioactivity, and 78% had become differentiated in their view as radiation as a transferrable contamination. In contrast only 6% of students remained undifferentiated in their views on radiation as a material, 17% remained undifferentiated in radiation compared to radioactivity, and only 8% remained undifferentiated in their view as radiation as a transferrable contamination. At this point, however, the number of students who were partly differentiated had grown considerably from the beginning of the semester. Twenty-two percent of students had become partly differentiated in their views on radiation as a material, 25% had become partly differentiated in radiation compared to radioactivity, and 14% had become partly differentiated in their view as radiation as a transferrable contamination. By looking at the data we could see the students who were part way between the two views were on their way to becoming differentiated and were expressing some views and thoughts that did not align with the scientific view of radiation, but had shown they had grasped the majority of the scientific views of radiation. We think these students were in transition to the differentiated view.

Discussion

Pre-instruction results

We have found that the undifferentiated view is extremely common among students beginning this class! Roughly 91% of 33 students began the class with undifferentiated thinking about radiation. Some students who previously had been taught about radiation nevertheless remained undifferentiated.

We believe that the undifferentiated view is widespread across many populations, cultures, and occupations. Not only has previous research identified the undifferentiated view in German, Dutch, and British students, but it is also quite evident in the words of many journalists who regularly refer to "the cloud of radiation [sic] from Fukushima" and some who have published articles in respected periodicals[8] (Note: Fukushima emitted a cloud of radioactive dust - this dust is still emitting radiation worldwide. But radiation itself from the reactor can only travel a few miles at the most so there was no "cloud of radiation").

Differentiating radiation

The RBI materials clearly helped students reconsider and replace their undifferentiated views with more sophisticated views of radiation. This appears to have taken place 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.

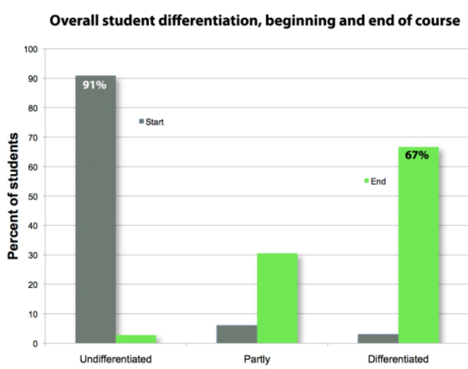

Figure 6: Percentage of overall student differentiation pre/post

As shown in Figure 6 the majority of students successfully differentiated radiation from radioactivity at the end of the unit. The three facets of the undifferentiated view are clearly connected - more often than not, students were fully differentiated on all three facets. However, some students in transition 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 distinct from each other.

We noted that the differentiation process takes place gradually over many hours of instruction and is not easy for most students. We believe this is because students must construct largely new understandings and abandon old ones. According to Dykstra[10], concept differentiation is a category 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. Making such a change 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 after it has been shown to be untenable.

All three of these characteristics are present in our classroom:

The ontological shift is clearly an issue for differentiating radiation from radioactivity. Students must change their thinking from "radiation as stuff" to "radiation as a process" since it consists of high speed particles flying away from nuclei.

We have witnessed much student confusion and uncertainty at times in the classroom. This was evidenced in students having difficulties with making sense of representations in simulators and with formulating new explanations for observed radiation phenomena.

We repeatedly found examples of students returning to old ideas, particularly the idea of contamination by radiation, or "the dirt theory". At certain points later in the course we expected students to say that radiation can't make other objects radioactive because the students had earlier tested objects by taping them to radioactive disk sources and they found that the victim objects never became radioactive. In the same lesson some groups tested the containers that had held the disks for five years and found these were still not radioactive. Furthermore, students had also investigated atoms in depth and had concluded that only those atomic nuclei with the wrong proton/neutron balance, or nuclei with more than 83 protons, would emit radiation. Nevertheless, some students persisted in saying that a stronger radioactive source, or longer amount of time exposed to the radioactive source would cause a victim object to become radioactive itself. This “transfer idea” was tenacious and continued to be resurrected by a minority of students in the class.

For example, on an exam late in the unit, students were asked if an apple would become radioactive after having many sealed radioactive sources taped to it while it grew on a tree over the summer. Only eleven percent of the class incorrectly said that it would become radioactive and 89% answered correctly. However, when asked how apples in Japan had become radioactive, an additional 28% of the students gave various incorrect (and undifferentiated) explanations of how this could happen. Only 64% of the class answered this correctly.

Incorrect student responses:

> "[Japanese apples] could only be radioactive if they had particles of radiation in them".
>
> "The cell structure of the atom was changed due to the damage caused by overexposure to super high levels of radiation".

Correct student responses:

> "Radioactive atoms have to be inside the fruit in order for it to be radioactive. If some of the nutrients from the water or soil were radioactive, the atoms from those nutrients could get into the apple, making it radioactive".
>
> "This happened because of the radioactive water getting into the soil, thus affecting the plant life".

Although we have shown that a majority of non-science majors can come to understand radiation meaningfully, we must also reluctantly conclude that understanding ionizing radiation and its interaction with matter is rendered significantly more difficult than one would hope because of the necessity of differentiating radiation from radioactivity and because of other learning difficulties beyond the scope of this paper.

The importance of differentiating

Differentiation is essential to understanding radiation at a basic, conceptual level. In order to reason about the interaction of radiation with matter and to understand how ionizing radiation can cause cancer in small exposures or burns and death in large exposures, students must be thinking about radiation as particles that ionize atoms. The undifferentiated view interferes with the scientifically accepted idea that radiation only harms tissues but does not colonize or propagate inside other objects. Thus, those students who had not differentiated had additional difficulties later in the course 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[9] found that students who differentiated radiation from radioactivity tended to be much more successful with understanding ionizing by radiation. The correlation between the two - 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 had greater difficulty forming conceptual mental models of the ionization process in which alpha and beta particles knock electrons out of many atoms and break molecular bonds. These difficulties persisted for undifferentiated students despite explicit experiences with those phenomena using the Atom Invaders and Tracks simulators.

Based on our observations of the initial undifferentiated view and persistence of specific undifferentiated concepts after instruction in the students within our courses, it can be presumed that the general population is undifferentiated as well, and therefore will have difficulty thinking effectively about radiation.

In a nuclear emergency such as the Fukushima disaster, officials and populations must act appropriately to minimize harm to humans and the environment. Politicians may not have working understandings of radiation - chances are that many have not differentiated radiation from radioactivity and these officials would have weak understandings of the physical situation. Would they know how to make the correct decisions? Populations at risk would not know the degree of emergency based on basic information about dose rates and wind directions and they may not act in their own best interests.

At other times, stakeholders who are making decisions about starting new nuclear plants, approving uranium mines, disposing of wastes, and mitigating environmental radiation problems should be guided by not only accurate information but also by useful understandings of radiation, its causes, and its risks. These times call out for widespread radiation literacy. The challenge of achieving this will require carefully designed learning activities at the level of intensity and duration of our trial testing course.

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