Student Understanding of Half-life and Background Radiation

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Abstract

We have been studying the conceptual understanding of high school students about radioactivity, particularly regarding background radiation and half-life. We have seen that it is difficult for learners to grapple with the idea that random behavior of individual atoms can give rise to predictable patterns in the collective, and many students have said both on the Stochastic World of Radioactive Decay Evaluation (SWORDE) and in interviews that, if you are looking at an individual atom, half of the atom will have decayed after one half-life. Our findings have indicated, however, that this idea (of individual atoms decaying in a predictably continuous manner) is often not a robust and intact mental structure; rather, in other contexts, the same students correctly discuss decay as being instantaneous and unpredictable. Approaches to teaching radioactivity that take this fluidity of student reasoning into account are desired. We created and validated an expanded version of SWORDE and are using the survey to assess "The Radiation Around Us", curriculum that does exactly that.

1. Introduction

Our research concerns the assessment of curriculum to teach students about radioactivity and ionizing radiation. Rather than attempt an exhaustive review of potential curricular materials, we have narrowed down our study to two research-based curricula, Inquiry into Radioactivity (IiR) and The Radiation Around Us (TRAU). This decision is supported by prior work conducted by the first author concerning not only what student ideas students bring with them to the classroom, but also the cognitive structure of those ideas. Specifically, the first author has found that student reasoning about radioactivity exhibits considerable context-dependency. Both IiR and TRAU anticipate and allow for this context-sensitivity. Since TRAU is more straight-forward for teachers to implement, the third and fourth authors are focusing on TRAU for their MS theses. The assessment involves, in part, student responses to a conceptual survey about radioactivity that was developed and validated in the MS thesis of the second author.

1.1. Theoretical Background: Tbe “Pieces” Model

In discussing theoretical frameworks for modeling student ideas, Scherr contrasted the “Misconceptions” model with the “Pieces” model (Scherr, 2007). Whereas the Misconceptions model attributes (often only tacitly!) a stable, rigid, and context-independent character to student ideas, the Pieces model (e.g., diSessa, 2009) explicitly treats student ideas as being potentially fluctuating, pliable, and context-dependent. Let us consider a research finding from mechanics for an example to illustrate this difference (Hammer, Elby, Scherr, & Redish, 2006). When a ball is thrown, there are two forces acting on the ball: a downward force from gravity and a force from air resistance that opposes the motion of the ball (which is often neglected in introductory mechanics instruction). When teachers ask students what forces are acting on the ball, however, it is not uncommon for students to answer that there is a downward force due to gravity and, in addition, a force from the hand which stays with the ball and becomes smaller and smaller as the ball’s speed decreases. If students had a “misconception” in the sense of a stable, rigid, and context-independent idea that “motion requires force”, then it should be the case that, when students are asked about the forces on the ball at the top of the trajectory (where the ball momentarily comes to rest), that students should now (correctly) say that there is only the downward force from gravity, as the force from the hand has decreased to zero. However, when many of these same students are asked about the apex of the throw, they change their reasoning to argue that "the downward force of gravity must be balanced by an upward force." The point is not that the students are wrong in both contexts (ball traveling upwards and ball at rest at the apex). Rather, the point is that the reasoning employed by students changed from context to context. This suggests that the students reasoning about this situation did not have a “misconception", but rather that their reasoning can better be described as "pieces"-like. For additional examples, we refer readers to (Hull & Hopf, 2021).

More generally, an analogy can help us visualize the difference between the two models of student ideas. In this analogy, the Misconceptions model might think of student's ideas as being like a tree, growing wild and deeply planted in the ground. This tree might be the "motion requires force" misconception described above, for example. The goal of instruction (the understanding that a <u>net</u> force <u>changes</u> motion) is represented in this analogy by a tower. In the Misconceptions model it follows that effective instruction would entail cutting down the tree, digging out the roots, and starting construction of the tower from scratch. The Pieces model, on the other hand, recognizes that what looks like a tree might actually be a composition of smaller knowledge pieces. Therefore, to have students leave the classroom with a tower-like understanding, it may be that all that is necessary is to rearrange some of the same knowledge pieces that were involved in establishing the tree. True, some of the knowledge pieces activated in the tree idea might not be helpful in constructing the tower and should be replaced with more appropriate knowledge pieces. The fact that many of the knowledge pieces, however, become activated both when thinking about the tree and about the tower indicates that these knowledge pieces are not inherently "right" or "wrong" in the way that a Misconception is wrong.

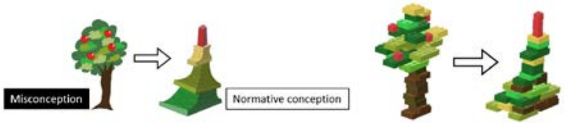

Fig. 1: Comparison of the Misconceptions (left) and Pieces (right) models of student ideas. Whereas the former model suggests that replacement (in this case of a tree with a tower) is efficient for student learning, the latter suggests that much of learning involves rearranging smaller knowledge pieces that students already have.

2. Student Understanding about Radioactivity can be Context-Dependent

Radioactivity decreases in a predictable manner characterized by the half-life. Holzinger found in her MS thesis, however, that even survey respondents who selected the correct definition for half-life failed to apply that knowledge in answering questions asking for a decision about radioactive material. For example, one of the items on Holzinger's survey is CLOSET, which is taken from the SWORDE (formerly known as FAROS) survey (M. M. Hull, Jansky, & Hopf, GDCP, 2022). This prompt asks respondents what they would do were their closet to become filled with I-131 gas. The survey item specifies that the half-life of the iodine is 8 days, and respondents are to choose after how many days they would open the closet to retrieve valuables from inside. When CLOSET was being developed, some respondents answered the free-response version of the prompt with something like "it would depend upon various factors", such as the concentration of gas in the closet and how the radioactivity of I-131 compares with background radiation, and we considered such a response to be appropriate. On the multiple choice version of the survey item that Holzinger administered, however, the most commonly selected response was "I would never open the closet." This is consistent with the findings of Alsop (2001) that learners have an image of radioactivity as being "quintessentially eternal". We think that making risk-benefit decisions regarding radioactivity is an important activity for citizens in a modern society; however, as indicated in this CLOSET prompt, it seems common for people to instead take on a stance of "avoid all radioactivity", which is delusional, since radioactive material is ubiquitous. Eijkelhof (1990) posited that the difficulty for people in making risk-benefit decisions about radioactivity is that radioactivity is stochastic in nature. The first author has argued that much content in physics is stochastic, and what may appear to be a wide range of student ideas in various topics may actually have a shared origin of difficulty in understanding randomness (M. M. Hull, Jansky, & Hopf, 2021). Specific to radioactivity, it is considered random when an individual atom will decay, and it is regarded as random whether or not the radiation emitted will ionize a victim molecule. To investigate whether student difficulties in radioactivity do arise due to an underlying difficulty in understanding randomness, and to see whether this difficulty is better described by the Misconceptions or Pieces model, the first author conducted seven semi-structured think-aloud interviews in 2018.

One of these interviewees, Bailey (all names are pseudonyms) demonstrated an awareness of the random nature of radioactivity in the interview. Bailey explained that "Atoms don't follow a scheme… ten can fall apart at once, and then in the next two seconds, only one." Nevertheless, Bailey had difficulties regarding how predictable rules (such as half-life) can emerge from such randomness (M. M. Hull & Hopf, 2020; Michael M. Hull & Nakamura, 2018).

During the interview, the first author had Bailey draw the decay of a single Radon-222 atom as time passes. Bailey made the sketch shown below in Figure 2 and explained that the decay must take place at some point before the half-life (roughly 4 days). There are various ways to interpret this data. One possibility we can consider is that Bailey did not understand what is meant by the physics term "half-life". Perhaps Bailey thought it means "life-time", such that a Rn-222 atom cannot live longer than 4 days. This idea, however, is problematic, in that earlier in the same interview, Baily demonstrated understanding about what "half-life" means in the context of considering a radioactive sample. In particular, Bailey correctly said that half of a sample of such atoms will remain after one half-life.

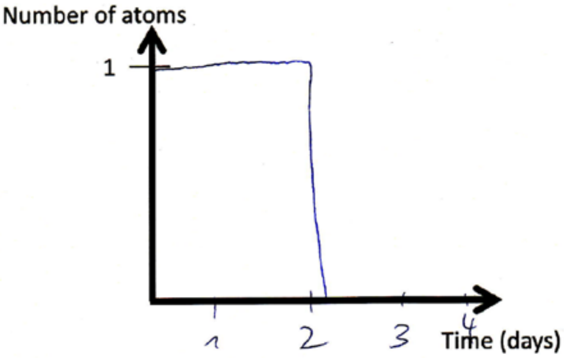

Fig. 2: Bailey's sketch to show the decay of a single Rn-222 nucleus as time passes. At this point in the interview, Bailey specified that the decay must happen at some point prior to the half-life (approximately 4 days).

At this point of the interview (drawing the decay of a single nucleus as time passes), however, Bailey treated the "half-life" as a special day for the constituents as well as for the radioactive sample: "When I flip a coin, the probability that I get a tails is 50% but an atom has this specific amount of time. After that, it *will* break apart (emphasis Bailey's)."

In general, Bailey's reasoning about the randomness inherent in radioactive decay was context-dependent throughout the hour-long interview. During this interview, the first author had Bailey consider and compare several analogies involving flipping coins. After the last analogy, the first author invited Bailey to revisit previous answers by asking "how confident are you with your previous answers?" At this point, Bailey changed the graph for the decay of the single atom (Figure 2) to no longer be restricted to lie within one (or even two) half-lives. We might be tempted to say that the succession of analogies succeeded in "cutting down the tree" about half-life being a "special day" for the individual unstable nucleus. However, when the first author then asked Bailey an isomorphic prompt ("isomorphic" meaning that two or more prompts can be answered correctly with the same conceptual understanding, despite differences in surface features), Bailey reverted back to thinking of the half-life as being a special day for the individual atom. Specifically, the first author asked Bailey which day the Rn-222 atom would be most likely to decay. Rather than saying "well, as I just learned, it is random and could take place at any point in time," Bailey instead answered "on the third day… on the fourth day, it is like fifty-fifty, so it might already be gone." Again, Bailey was using the "special day" way of thinking.

These interviews served as motivation for the Stochastic World of Radioactive Decay Evaluation (SWORDE). SWORDE (formerly known as FAROS) consists of three isomorphic prompts that can all be answered satisfactorily with the conceptual understanding that, despite the usefulness of half-life for making predictions about radioactive samples, it is random when an individual unstable nucleus will decay. The prompts are two-tier, in that respondents are first asked to answer the item (answer tier) and then asked to select an explanation (reasoning tier) that led to the answer selected. Both tiers for all prompts are closed form (multiple choice or multiple select). The first of these prompts, MANY vs ONE or MvO, involves thinking about the decay of a single nucleus as time passes (equivalent to the interview prompt featured in Figure 2). The MANY part of this prompt reads:

- Iodine-131 is an example of a radioactive atom. It has a half-life of 8 days, so if one begins with a large number of these atoms, then half of the atoms will have transformed into a different atom after 8 days.

  Imagine that there are 100 million Iodine-131 atoms in the beginning. How much Iodine-131 will have not yet transformed after … i. 8 days? ii. 16 days? iii. 24 days?

Although many students answered this three-part question correctly, the subsequent three parts (ONE) proved more challenging:

- Imagine that there is just a single Iodine-131 atom in the beginning. How much Iodine-131 will have not yet transformed after … i. 8 days? ii. 16 days? iii. 24 days?

Many students, like Bailey, attributed the status of a "special day" to the half-life when answering not only MANY, but ONE as well. Some respondents selected the options "0 atoms", "0 atoms", and "0 atoms", consistent with Bailey saying that the decay must take place before the half-life. Much more common, however, was thinking that, after one half-life, half of an atom would remain. This "half-atom" idea has been described elsewhere in physics education research (PER) (M. M. Hull & Hopf, 2020; Jansky, 2019; Klaassen, Eijkelhof, & Lijnse, 1990). We see this idea that what is true for the collective (half "gone" after one half-life) is also true for the constituents making up that collective as being an example of a "Level Confusion" (LC). (Wilensky and Resnick, 1999). Since our interviews had indicated that such LC's are not context-independent Misconceptions, but rather that student reasoning can fluidly shift, we included not only the MvO prompt in SWORDE, but two other isomorphic prompts as well. One of these other two prompts is CAGE, which asks what day the atom is most likely to decay (Jansky, 2019). The final prompt is ANT, where survey respondents consider a concept cartoon of students making claims about the radiation sent out by a radioactive stone to an ant who is standing motionless nearby, first when the stone contains a trace amount of radioactive material, and then when the stone contains a huge amount of radioactive material. These three prompts are isomorphic in that students can answer satisfactorily if they understand that it is random when an individual atom decays. All three prompts can also be answered with a response indicating an LC. For example, students who say that there would be no difference whether the stone contains a trace or huge amount of radioactive material were coded as indicating an LC on this prompt: whatever is true when there are many radioactive atoms together must also be true when there are only a few together.

Isomorphic prompts were made popular to the PER community by Singh, who used them to demonstrate that student reasoning can vary from prompt to prompt, indicating the context-sensitivity of student ideas. Singh (2008) wrote:

> “From the perspective of knowledge in pieces, problem context with distracting features can trigger the activation of knowledge that a student thinks is relevant but which is not actually applicable in that context… students activat[e] different resources to deal with somewhat different contexts which experts view as equivalent”.

A student with a "misconception" (in the sense of it being a stable cognitive structure that is not context-dependent) should answer consistently across the three prompts with the same wrong reasoning: "What is true for the radioactive sample is true for the individual atom."

The first author administered the final version of SWORDE online (using Survey Monkey) from Nov. 9th 2020 to March 24th 2021. After data cleaning, N = 234 (17-18 year olds who had already learned about half-life) remained.

On ANT, we assigned an LC code to students who selected "My answers would not change" [whether the stone has a trace or abundant amount of radioactive material in it] AND/OR if the respondent selected "There is no difference, except that the stone sends out radiation longer." On CAGE, we assigned a code of LC if respondents selected "After the half-life, half of the atom will have transformed" AND/OR "The atom transforms on the day of the half-life" AND/OR "The atom transforms continuously" on the reasoning tier. Finally, on MvO, we assigned an LC code if respondents selected "Half an atom" after one half-life for ONE on the answer tier; AND/OR selected "After the half-life, half of an atom will have transformed" on the reason tier; AND/OR selected "0 atoms" after one half-life on the answer tier of ONE while also selecting "One cannot have half an atom" on the reason tier.

We found that out of the N = 234 respondents, 193 (82%) answered MANY correctly. Of those 193 students, 116 students (60%) received an LC code on ONE. Looking at all three prompts, most respondents (224, 96%) showed evidence of LC on at least one of the three prompts (see Figure 3, below). However, only 104 (44%) exhibited a level confusion consistently across all three prompts. For the majority of students indicating a level confusion, it seems inappropriate to describe them as "having a misconception". Rather, this response pattern is better described by the Pieces model (Michael M. Hull, Jansky, & Hopf, PRPER 2022).

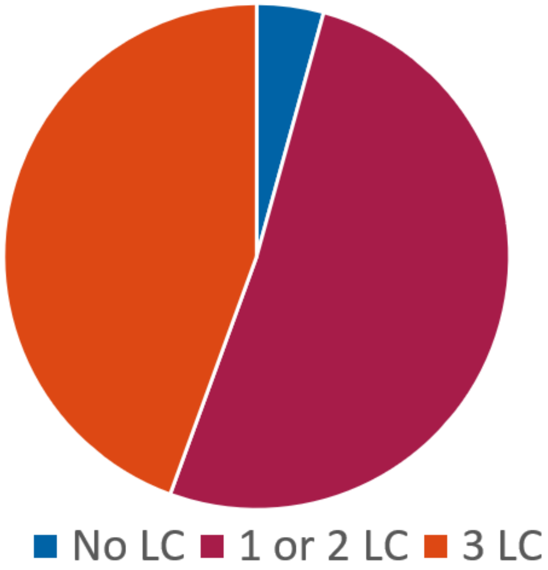

Fig. 3: Most of the N = 234 students indicated a level confusion (LC) on at least one of the three isomorphic prompts. However, less than half of those students consistently demonstrated a level confusion throughout the survey.

3. Radioactivity Curriculum that Allows for Context-dependent Reasoning

There are two curricula for teaching about radioactivity that have caught our attention as they do not attempt to “chop down the tree” of student ideas. Rather, they respect student ideas and allow them to fluidly shift in response to experimental outcomes and peer discussions. These two curricula are The Radiation Around Us (TRAU), an excerpt from Yamamoto’s curriculum “Radiation and Sievert” (Yamamoto, 2011) developed in the MS thesis of Goda at the University of Kyoto, and Inquiry into Radioactivity (IiR), developed by Johnson in the USA (M. M. Hull & Johnson, 2021; Johnson, 2013).

IiR is designed for non-science majors taking a physical science course at a USA university. The instruction on radioactivity lasts for one semester, and even this is rarely enough time to complete the IiR materials. In each lesson, students work in groups of 3-4 to conduct experiments with radioactive materials and Geiger Müller counters. As the name suggests, it is an inquiry-based approach to learning, where the instructor is not the distributor of knowledge, but rather the facilitator of the group- and class-based discussions. Only after students have come to a consensus do they record key ideas of what they learned in that lesson. There are several difficulties with implementing IiR in an Austrian high school. First off, not every school has a Geiger Müller detector to measure ionizing radiation, let alone one for each group of students, as proposed by IiR. Most high schools are not permitted to have radioactive materials at all, even those that are only marginally above background radiation. Over the past few years, the first author and his pre-service teachers have worked to surpass these challenges by choosing indispensable parts of IiR to compress into three 50-minute-long lessons and to create videos of the experiments that students can watch and discuss in their groups in cases when hands-on equipment is not available. There is an additional challenge with IiR in terms of its dissemination in Austrian high schools, however. Although the inquiry spirit is perhaps ideal in terms of students coming to reach an understanding of radioactivity in a way that feels organic to them (as opposed to being knowledge that they must merely memorize from the teacher, after rejecting their own ideas), it is perhaps the most challenging for teachers—especially novice teachers—to implement. Here is where TRAU shows a strong potential benefit.

Whereas IiR covers (at one point or another) virtually all of the Austrian Lehrplan, TRAU focuses on building awareness that we are continuously surrounded by ionizing radiation: it is not just something we find around Fukushima and Chernobyl; rather, we ourselves are radioactive. This is something that is rarely learned satisfactorily in high school. The second author created, validated, and administered an online survey to N = 386 adults (who had learned about radioactivity in school) who were not working in a radioactivity-related field. This survey, which included some items from SWORDE, also included the question "which of the following would make a radioactivity detector click?" (with the correct answer being to check all 10 items in the list). She found that only about 10% of respondents said that a school child would do so (see Figure 4, below).

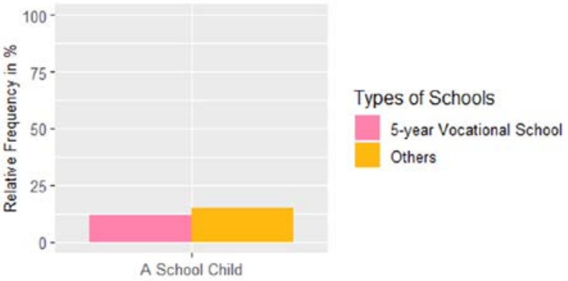

Fig. 4: Regardless of what kind of school the survey respondent had graduated from, only about 10% correctly indicated that a school child would make a radioactivity detector click.

TRAU respects and encourages fluidity of student reasoning while still being relatively easy for teachers to implement. TRAU is an instructional module created in the Hypothesis–Experiment Class (HEC) style. In general, HEC expects that an individual may simultaneously have multiple ways of thinking about a given situation. As the HEC founder, Itakura, wrote:

“Even students with minimal knowledge of the topic at hand will nonetheless probably have, at least, some naïve ideas regarding the topic. These may not be very logical and may even be an amorphous understanding with fluid interpretations” (2019).

HEC, TRAU included, follows a cyclical process that begins with students making a personal expectation about what the result of a proposed experiment will be. Unlike in IiR, where students are given freedom to design and interpret their own experiments, HEC has the experiments printed ahead of time in the worksheets students receive. Part of the teacher’s role is to ensure that the outcome of the experiments is unambiguous to students. After students have chosen their expectation from a multiple choice question that is also printed in the worksheets, the teacher conducts a public tally. Although student names are generally not attached to the votes, a tally of how many students chose option A, B, or C is written on the board. At this point, a discussion ensues between the students. Here again, the teacher plays a role by calling on students, even if they are not raising their hands, and by ensuring that all ideas are heard. Although students must participate during this whole-class discussion, it is sufficient for them to respond with statements like “I chose A, but it was just a guess” or “I chose A because my friend chose A, and she is usually right about these kinds of things.” For example, one of the nine Problems for which students select an expectation involves the situation of climbing a tall tower and seeing how the gamma radiation detected in the hand-held gamma detector will change. During the discussion stage of this Problem, we often hear students justify their selections in terms of the results of the experiments in the previous Problems of the lesson. Students will argue things like “well, we have seen that the ground is a source of radiation, and we are going farther away from the ground, so the radiation should decrease” or “we have seen that on the sea or above a swimming pool, the radiation level is less, so I think the humidity in the air will similarly act as a shield”. Following the discussion, the teacher invites students to change their prediction if there was anything that had convinced them during the discussion. These changes of prediction are also tallied on the board. Finally, the experiment is conducted or (in the case of TRAU) the results of the experiment are disclosed to students in the next worksheet they received from the teacher. This next worksheet also contains marginal (if any) explanation about the cause of the experimental outcome before presenting students with the next Problem to repeat the cycle.

Throughout this process, the teacher does not correct errors in student reasoning, but rather leaves them as they are, waiting for students to accept new information through a succession of results from experiments that are carefully selected and arranged. Unlike in an inquiry style of learning, the whole class format and the pre-determination of experiments poses less of a challenge on teachers. At the same time, student ideas are not rejected by the teacher. As Itakura wrote in comparing HEC with more traditional approaches,

> “…the student will often spin out a newer interpretation … just to incorporate the new fact. And yet the teacher and textbook [in traditional instruction]… simply conclud[e], ‘So we can see that these facts lead to such and such.‘ In cases such as this, the teacher has brutally forced a theory on the student...” (2019).

4. Outlook

In both interviews and surveys, the first author has documented that student reasoning about radioactivity can be fluid and context-sensitive. As such, effective instruction about radioactivity should not aim to “cut down the tree” of student ideas but rather create a space where pieces of student ideas can shuffle about in response to experimental outcomes and peer discussion until crystallizing organically into the “tower” of normative knowledge we desire our students to learn. An inquiry style of teaching like IiR might be ideal from the student perspective, but the group-based student-directed interactions are hard for novice teachers to facilitate. TRAU is a viable alternative, but it needs to be tested. To carry out this assessment, we utilize a survey developed by the second author (see Holzinger & Hull, 2022 for details). So far, unfortunately, it seems that TRAU is not as effective as hoped for helping students recognize that they are radioactive, but it does seem that the HEC goal of student enjoyment is satisfied in TRAU (see Jeidler, Wintersteller, & Hull, 2022). At present, the claim that TRAU is relatively easy—even for novice teachers—to implement is a hypothesis in need of testing. Based upon preliminary findings with a novice high school teacher who taught with TRAU three times, it seems that the HEC goal of reliable learning outcomes may be satisfied (see Wintersteller, Jeidler, & Hull, 2022).

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